

CRANFIELD UNIVERSITY

JINXIN GU

AIRCRAFT HEAD-UP DISPLAY SURFACE GUIDANCE SYSTEM

SCHOOL OF ENGINEERING
MSc By Research

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Academic Year: 2012 - 2013

Supervisor: AL Savvaris
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the degree of Master of Science

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ABSTRACT

The continues growth in aviation and passenger numbers is putting more pressure on airports to become more efficient in order to reduce the number of delays due to external factors such as weather, pilot deviation/errors and airport maintenance traffic. As major hubs (e.g. Heathrow, New York or Paris) expand in size to accommodate more traffic; aircraft surface movement and management become more complex and the margin for error is even lower. The traditional airport traffic management tools in large airports are increasingly stretched to the limit in meeting safety and traffic throughput requirements. This presents a huge challenge to the efficiency of airport operations because of the increased number of departures and arrivals at those airports. New technology for surface movement needs to be implemented in order to increase the safety and airport capacity. The federal aviation authorities in the USA was first to introduce the concept of Advanced Surface Movement Guidance and Control System (A-SMGCS) to address this problem in commercial airdrome operations. The system facilitates pilot recognition of the route designated by the traffic controllers and uses warning information to make them aware of any potential deviations/incursions. The system is introduced to enhance the efficiency of surface movement by increasing the aircraft taxiing speed and reducing any pilot errors during bad weather conditions.

This thesis focuses on the surface guidance system for aircraft equipped with head-up display. A simulation model of the virtual environment using FlightGear and Simulink is developed based on the study of a moving map and surface guidance system for Head-Up Display (HUD) to assign the route, guide the aircraft on the designated taxiway and avoid potential conflict with other aircraft. A method of generating an airport in FlightGear and driving an airport moving map to rotate and move is also illustrated which includes the data processing flow chart and system flow chart. The Ordnance Survey National Grid and world coordinate system is discussed and used to transform from GPS latitude and longitude data to the position on Nation Grid.

There is also an explanation of the 3D viewing process to generate the virtual taxiway geometries on the HUD. The communication between the traffic console and airplane is also discussed.

Keywords:

Airport, guidance, runway incursion, routing, surface movement, taxiway.

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LIST OF ABBREVIATIONS

ACM	Airport Certification Manual
A-SMGCS	Advanced surface movement guidance and control system
ATC	Air Traffic Controller
CPA	Closest Point of Approach
CRT	Cathode-Ray Tube
CV	Convergence
CVV	Canonical View Volume
EC	European Commission
EFB	Electronic Flight Bag
EFS	Electronic Flight Strips
EMM	Electronic Moving Map
FDM	Flight Dynamics Model
FOV	Field-Of-View
GB	Grid Bearing
GD	Guidance Direction
GIS	Geographical Information System
GNSS	Global Navigation Satellite System
GPL	General Public License
GUI	Graphical User Interface
GUND	Geoid Undulation
HD	Heading
HMI	Human Machine Interface
HUD	Head-Up Display
I/O	Input and Output
IFOV	Instantaneous FOV
IMM	Integrated Moving Map
MSL	Mean Sea Level
ND	Navigation Display
NLR	National Aerospace Laboratory
OANS	On Board Airport Navigation System
OE/D	Operational Errors
OHU	Over Head Unit

PD	Pilot Deviations
PZ	Protected Zones
SGS	Surface Guidance System
SMGCS	Surface Movement Guidance and Control System
SRTM	Shuttle Radar Topography Mission
TAXI-CPDLC	Controller Pilot Data Link Communication with Taxi operations
TB	True Bearing
TFOV	Total FOV
TIS-B	Traffic Information System Broadcast
T-NASA	Taxiway Navigation And Situation Awareness
TSO	Technical Standard Order
V/PD	Vehicle/Pedestrian Deviations
VDL-2	VHF Data Link
WGS84	World Geodetic System 1984

1 INTRODUCTION

1.1 Project Background

The current growth in air traffic reflects the development of the aviation industry. This increased quantity of movement in the large commercial airport intensifies the need for deliberate taxiing of the aircraft in order to avoid incursions on the taxiway and runway. This slowness of movement on the surface restricts the capacity of international airports especially in low visibility under adverse weather conditions. Although plenty of investment is put into the development of airport facilities, FAA reported that between 2006 and 2009, there were on average 917 runway incursions each year. Of these, in 2009 for example, 63 per cent of runway incursions were caused by pilot deviations, compared with 37 percent induced by operational errors and vehicle/pedestrian deviations [1]. The pilot deviations may occur due to poor weather conditions, ambiguous communication between flight crews and traffic controllers, loss of situation awareness and blurred marking at the airport.

Advanced surface movement guidance and control system (A-SMGCS) is introduced to the airport traffic management to address these deviations. A-SMGCS is widely developed in providing guidance, surveillance for aircraft control in commercial airdrome operations. But potential improvements are still necessary to enhance the efficiency of this advantage system. An on-board guidance system is introduced to enhance the situation awareness of pilots and to decrease the pilot deviations caused by the low visibility and ambiguous communication between pilots and traffic controllers. This research tries to find an available method for aircraft guidance using on-board system.

1.2 Aim and Objectives

The aim of this research is to develop a simulator for the head-up display Surface Guidance System (SGS) to assist the pilot to taxi in the low visibility weather conditions.

The objectives of this research are as following:

To review and understand the principle of current technologies that introduced to the head-up display system;

To develop a head-up display framework for surface movement guidance in airport and to integrate this framework with the head-down display system to enhance the guidance efficiency;

To integrate the guidance information on the head-up display and insert the Cranfield airport map in the head-down display;

To achieve the pilot evaluations with two professional pilots for this head-up display guidance system.

1.3 Contributions

This research focuses on the on-board head-up display surface guidance system, the contributions of the research is as below:

An ad-hoc methodology to display the virtual taxiways and holding points on the HUD simulation based on the Ordnance Survey airport map was developed to guide taxiing. The Ordnance Survey airport map was used as the data base to generate the HUD 2D geometries and airport 3D model. The virtual taxiways and holding points displayed on the HUD can coincide with the taxiway edges and holding points outside the cockpit from the viewpoint of the captain. The pilot can have a virtual intuitive outside scene from the geometries displayed on the HUD.

A guidance line designated by the traffic controller was introduced to the HUD SGS. The guidance line was displayed on the HUD and coincided with the taxiway centreline outside the cockpit to assist the pilot to taxi to the destination.

A virtual taxiway clearance bar on the HUD was introduced to indicate the position of the hold point designated temporarily by the traffic controller. The clearance bar can also be used to prevent the pilot's mistake by popping up a large size of 'STOP' warning information on the centre of HUD if pilot passed the hold point without the permission from the traffic controller.

1.4 Thesis Outline

The following table presents the outline of the thesis.

Table 1-1 Thesis Outline

Chapter	Title	Outline
Chapter 1	Introduction	Present project background information and objectives of this project and provide an outline structure.
Chapter 2	Literature Review	Introduce the current traffic situations in airport, government request and industry criteria, current technical solution for surface guidance system using head-down display and head-up display.
Chapter 3	Methodology	Provide the methods to implement guidance simulation in FlightGear and Simulink. Present the arithmetic of geometries on the head-down display and the head-up display using GPS to guide the pilot enhance situation awareness when taxiing on the airport in FlightGear simulation. The traffic controller console is also introduced to control the surface movement.
Chapter 4	Simulation Results and Discussions	States the simulation results of the head-down display, head-up display and the traffic control console and the airport generated in FlightGear.
Chapter 5	Conclusions and Future Work	Concludes the simulation and programming work in this phase and states the future work of guidance

		system using head-up display and trail on the airport.
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2 LITERATURE REVIEW

2.1 Surface Movement Situations

The total sum of airports or airfields worldwide was approximately 44,000 by 2012. The top ten airports by passenger numbers included Atlanta (ATL), Beijing (PEK), Chicago (ORD) and London (LHR), averaging about 64 million passengers in 2010. Clearly, such large number of passengers directly result in a huge number of aircraft movement in these airports, for example, there were nearly 500,000 aircraft movements in Heathrow International airport during 2010.

ICAO defines a runway incursion as any occurrence at an aerodrome involving the incorrect presence of an aircraft, vehicle or person on the protected area of a surface designated for the landing and take-off of aircraft [2]. EUROCONTROL, a European organisation for the safety of air navigation, stated that the total quantity of runway incursions reported in 2010 increased considerably by 26 per cent according to the preparatory data in the Annual Safety Report 2011. And the occurrence of runway incursions per million aircraft movements more than double from about 3 in 2009 to 6.5 occurrence in 2010 [3]. Although the quantity of the runway safety related accidents has dropped significantly from 2011, there are still nearly 45 per cent of accidents related to runway safety [4].

FAA has categorised three types of runway incursions: Operational Errors (OE/D), Pilot Deviations (PD) and Vehicle/Pedestrian Deviations (V/PD) according to the illegal operators. Operational Errors relate to the air traffic controller who commands an action that results in less than the required minimum separation between aircrafts or results in entrance into a closed runway. Pilot Deviations are caused by an action of a pilot who violates any Federal Aviation Regulation. Vehicle/Pedestrian Deviations are related to the unauthorised entrance into airport movement areas by pedestrians or vehicles [1].

The distribution of runway incursion type in 2009 is illustrated in Figure 2-1.

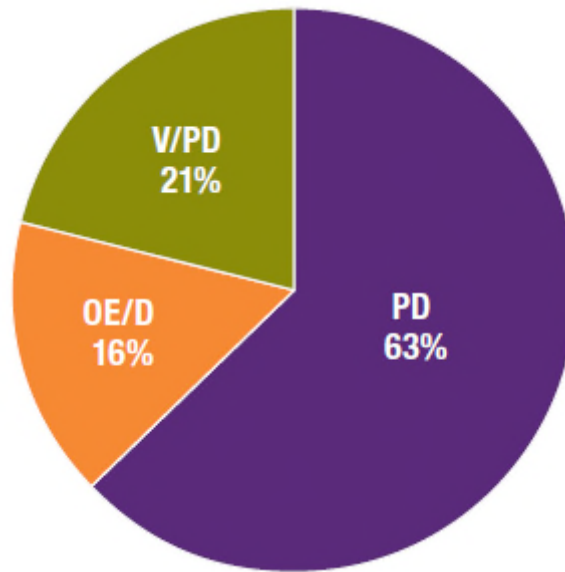


Figure 2-1 Distribution of runway incursion type in 2009 [1]

The Pilot Deviation is the most significant type of runway incursion: nearly two thirds of runway incursions are related to the action of the pilot. Several reasons result in Pilot Deviations, including poor communications between the traffic controllers and pilots, loss of situational awareness of airport traffic, pilots unfamiliar with the airport diagram, and severely low visibility weather conditions. Improvement of the above factors will benefit the safety of the traffic movement on airport.

2.2 Government Requirements

FAA has published an advisory circular AC 120-57A describing for the standards and providing guidance in the development of surface movement guidance and control system plan used when the visibility is less than 1,200 feet runway visual range in Dec. 19th, 1996 [5]. Although this advisory circular has requested the airport provide the low visibility taxi route charts to flight crew and ATC personnel, it focuses attention on the airport facilities, such as, traffic light systems, holding position markings and airport surface detection equipment to enhance the guidance and control system.

Notice of Proposed Rulemaking published by FAA in Nov. 2nd, 2011 suggests to change Part 139 to require the SMGCS program to be a part of the Airport Certification Manual (ACM) to increase the safety of surface movement [6].

2.3 Current Surface Movement Guidance System

In order to minimise the possibility of runway incursions and maximise the safety of surface movement in airports, there are several organisations such as ICAO, EUROCONTROL, FAA, NASA engaged in the Advanced Surface Movement Guidance and Control System project.

In the majority of airport guidance systems, the movement guidance on the aerodrome surface is performed according to Surface Movement Guidance and Control System (SMGCS). It is normally implemented by traffic controllers through instructions or manually operating stop bars and taxiway segmented switchable centre line lights [7]. Ground controllers use radio telephony communication with pilots to instruct the routing plan, taxiing sequence, predefined route from the gate to the runway holding point for take-off or from the landing runway to the stand while the flight crew rely on the visual aids such as light system, signage and markings to follow the instructions issued by the controllers. But these guidance operations may be obstructed due to loss of visual cues in low visibility conditions, navigation problems raised by deficiencies light system and marking, or due to ineffective communications between ground controls and the pilots.

The A-SMGCS Level 1&2 project was focused on a reliable automatic surveillance of the complete aerodrome traffic and an automatic runway incursion warning [8]. Consequently, traffic controllers obtain more traffic situation awareness of the surface movement on the aerodrome including its arrival and departure areas. Specifically, it supports the controllers to detect any potential critical traffic situations occurring on the runways. For the guidance function of A-SMGCS Level 2, Global Navigation Satellite System (GNSS) technology is used on the vehicles showing its position in an airport map with taxiways, runways, obstacles in order to minimise navigation mistakes in low visibility conditions.

Compared to the SMGCS, the A-SMGCS enables the guidance function by, but not limited to, taxiway lighting, on-board equipment and ground infrastructure, enhanced with route planning service and surveillance service. The guidance function in A-SMGCS instructs pilots with clear indications to support them to follow a designated route from controllers. It provides guidance information for any authorised movement and can be used to assign all available route selections when aerodrome controls the inbound and outbound air traffic flows. It also support all flight crews and ground vehicle drivers to maintain situation awareness of their position on the assigned route [9].

The communication work load of controllers and pilots increases because of the traffic density growth in airports. All instructions are expressed by voice and repeated by pilots. Most pilots find that it is more difficult to taxi to a gate when the assigned route is changed with another route mid-stream. Pilots have to confirm their location at the airport and imagine the route assistant with airport paper charts. This led to the development of higher levels of an A-SMGCS services performed by European Commission (EC) project EMMA2 [8].

Planning, routing and data link communication become the operational concepts for higher level A-SMGCS services. Planning systems such as departure manager optimise the up to date information, and provide it to the controllers through Electronic Flight Strips (EFS). This solution on flight strips enables the controller to easily update and share flight plan data, and pass the flight strip to the next position. Routing function will calculate and optimise the taxi route for each aircraft. Then the taxi route can be electronically transmitted to the cockpit through Controller Pilot Data Link Communication (TAXI-CPDLC). This technical solution avoids misunderstanding of voice communication and saves time of radio communication between controllers and pilots. Electronic Moving Map is planned to as equipment on board to enable the flight crew determine their position. The routing information assigned by the controllers and surrounding traffic will also be shown on the electronic moving map transferred by VHF Data Link (VDL-2) using the Traffic Information System (TIS-B). A new onboard service named automatic onboard conflict recognition is introduced to

warn pilots of potential conflicts with other mobility. And Head-up Displays may become an alternative onboard guidance systems to increase the pilots situation awareness particularly in miserable weather conditions.

EMMA2 project states it has a significant contribution to improving safety and efficiency of airdrome operations by improving situation awareness of pilots and controllers, reducing of taxi time and unloading the voice radio channel [8].

2.4 Current Solutions Using Head Down Display System

The most common onboard technical solution for guidance is moving maps shown on the head-down displays. There are several industry criterions and requirements developed to standardize the design of electronic maps.

RTCA, Inc. sponsored as a Federal Advisory Committee by the US DOT Federal Aviation Administration is known as a US volunteer organization that develops technical guidance for use by government regulatory authorities and by industry. It published an updated Minimum Operational Performance Standards for the Depiction of Navigational Information on Electronic Maps (DO-257A), in June 2003 which supports the electronic depiction of airport surface situation awareness maps and vertical situation awareness displays. The updated version includes requirements and guidelines for the electronic depiction of airport surface diagrams, own ship, ground path and vertical profile aspects of the display and associated controls.

FAA publishes the Technical Standard Orders (TSOs) to guide the design and approval of airdrome moving maps. TSO-C165, Electronic Map Display Equipment for Graphical Depiction of Aircraft Position [10], which references RTCA DO-257A, contains the requirements for the approval of the surface moving map function specified by FAA. For better implementation of the TSO, Human Factors Research and Engineering Division of the FAA released a report, Human Factors Considerations in the Design and Evaluation of Moving Map Displays of Ownship on the Airport Surface in September,2004, providing additional guidance to supplement that specified in TSO-C165 and RTCA DO-257A with FAA regulations, industry documents, and general user interface

design principles that describe best design practices relevant to the design of the surface moving map displays [10, 11].

EMMA2 project develops the airport moving map to assist the outside visual evaluation of the own-ship situation, such as speed, direction and location on the map of airport. The moving map indicates the own-ship position related to airport geographic layout and aerodrome facility positions, for example, the light systems and marking positions which are referenced by traffic controllers [12]. After experimenting on the THALES avionics flight simulator, pilots recognised the improvement of situational awareness and surface navigation whatever weather conditions when equipped with the integrated moving map, because the moving map supplies an intuitive expression of the whole airport layout with scale changeable function, and displays the navigation help enables flight crew to catch next direction and destination or assigned routing, especially, it integrates the local other mobiles around own ship [7].

National Aerospace Laboratory (NLR) evaluated an autonomous Taxi Solution for airport operations during low visibility conditions based on a basic Closest Point of Approach (CPA) algorithm in 2011. The Protected Zones (PZ) in the CPA algorithm are used to surround all aircraft according to the size of the aircraft plus a safety margin. The CPA is detected by the state-vector of each aircraft pair. The time to CPA, tCPA, is used to determine the severity of the conflict. The alert requirement is graded into four levels to depict the alert level criteria according to the tCPA. The symbol colour displayed on the Navigation Display (ND) and the aural alert are both introduced as the Human Machine Interface (HMI) of the autonomous system [13].

Theunissen and Roefs developed an exocentric SGS display format by presenting the 3-D location of the vehicles in a 3-D airport environment on the head down display [14]. The routing information was integrated into the surface guidance display. The experiment indicated that the separate guidance and control references and the combined guidance and control references both could be usefully applied [15].

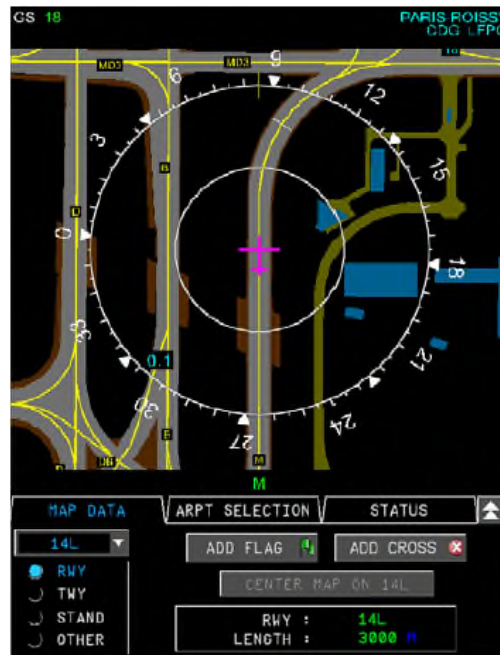


Figure 2-2 OANS display on MFD [16].

Currently, there are several manufacturers and research organisations participated in this advantage guidance concept and some of them provide available surface moving map products to the market, such as On Board Airport Navigation System (OANS) which has been used on Airbus A380 (as shown in Figure 2-2), SmartRunway (Runway Awareness and Advisory System) designed by Honeywell, and Jeppesen Airport Moving Map software and database for EFB (Electronic Flight Bags) systems shown in Figure 2-3. Although the data format of the surface moving map and customizable method of information depiction for these products have distinctions with each other, they are all compliant with the industry standards and approval documents, for example, TSOs, ACs [16]. However, to be different from the EFB which is installed separately from the navigation system, OANS and SmartRunway are installed and displayed on the MFD and integrated in the whole navigation system. If navigation system is crashed, EFB can still work as a backup navigation system.



Figure 2-3 Jeppesen Airport Moving Map on Class 2 EFB [16].

2.5 Current Solutions Using Head-Up Display System

As a pilot always taxis only at a velocity he feels comfortable with, slower traffic movement and loss of situation awareness will occur in low visibility weather conditions or when the pilot is unfamiliar with the airport layout. Surface Guidance System (SGS) is developed mainly to increase the flight crews' confidence level and guidance accuracy to avoid incursions, resulting in increased safety and capacity on the airport moveable area, particularly during night and low visibility conditions.

The SGS is designed as an upgrade software package for the aircraft fleets already equipped head-up guidance system. By integrating with the aircraft existing head-up guidance system, flight management system and navigation database, SGS can provide head-up display system standardized ground route on taxiway and runway.

During taxiing phases, the pilots are strongly dependent on the navigational aids equipped on the external airport surface outside the cockpit. Therefore, in order to increase the safety and efficiency of the surface movement, it is advisable to help the pilots to taxi during the low visibility weather conditions. However, as the SGS displays the route guidance by programming, it is very important to guarantee the accuracy and reliability of the guidance programming [17]. A plenty of researches associated with the efficient surface guidance

methods on the HUD have been performed by NASA, EMMA2 project and SGS suppliers, such as Rockwell Collins.

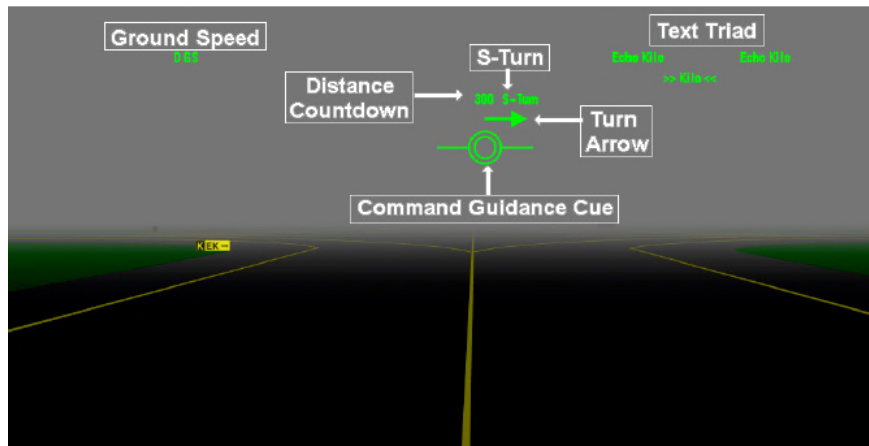


Figure 2-4 Command-guidance symbology [18]

NASA has simulated this head-up guidance concept with scene-linked HUD symbology for taxi and surface operations in T-NASA system [19]. They made a comparison in the following development among the Command-guidance (as shown in Figure 2-4), Situation-guidance (as shown in Figure 2-5), Hybrid symbologies and the No-guidance symbologies on the HUD for surface movement operations. The Situation-guidance symbology uses a plenty of triangles to indicate the runway and taxiway edges. The Smaller rectangles indicate the runway and taxiway centrelines. They found a taxi speed increase and a lowest deviation from the centreline with the help of the Situation-guidance and Hybrid symbologies on the head up guidance for surface movement [20]. Proctor also introduced a head-up guidance symbology similar to the T-NASA system, but with a vertical line in the centre of the display serves as a turn trend vector [21]. However, the scene-linked HUD symbols are similar to the taxiway lights on the edges and centre of the taxiways, the pilots may be confused by the scene-linked symbols and the real lights on the taxiways. Thus, other symbols to represent the taxiway edges need to be designed.

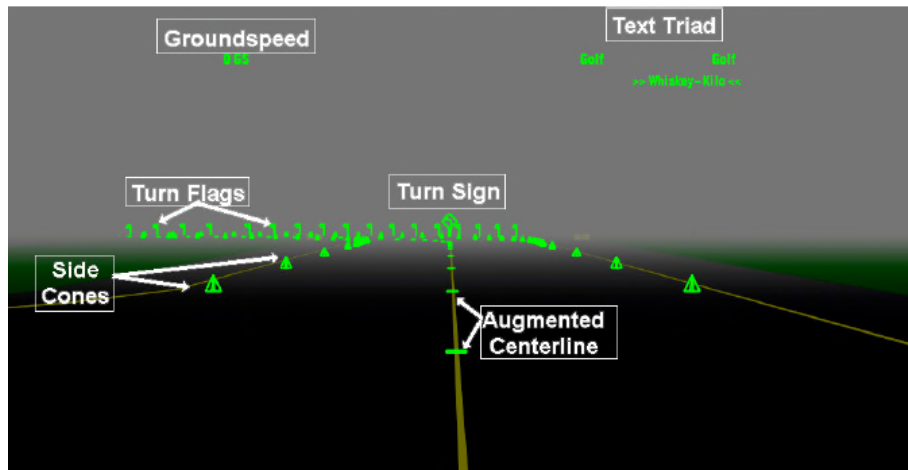


Figure 2-5 Situation-guidance symbology [18]

EMMA2 project also developed a HUD SGS with new symbols distinct from previous research to present information regarding the situation awareness and surface movement alerting indications on the HUD, and implemented appraisal on cockpit simulator. The EMMA2 team found that the captain almost never looked down at the integrated moving map as all route information and the associated taxiways was displayed on the HUD during the taxiing phase [7]. This HUD SGS integrated taxi route symbols, 2D top sight view to enable a overview of the aircraft location on the taxiway, aircraft self guidance symbols, and surface movement alerting indications such as message "On Runway" which is very efficient to remind the pilots to avoid runway incursions [7].

Rockwell Collins is developing a new Surface Guidance System integrated in head-up guidance system with new symbols format to facilitate pilots navigate on airport authorised area. By accessing the airdrome database, the surface guidance system can recognise the centre lines and edges of the current runway or taxiway the aircraft is operating on, and display virtual centre line, edge lines, signals and other symbols that overlay the actual airport taxiways, runways and signage. This extra situational awareness may enable the pilots to navigate more confidently and minimise the potential runway incursions. But too much information is displayed on the HUD, for example, all the centre lines of the taxiways are displayed. The pilots still has to receive the guidance information by radio as they may be confused by the centre lines displayed on

the HUD. Less confusion may result if the edges of the taxiways and only the centre line of the guidance route are displayed, hence the pilots just need to taxi align with the guidance route.

2.6 Communication with Data Link

TAXI-CPDLC (Controller Pilot Data Link Communication with Taxi operations) is developed to enable more efficient communication between the pilot and traffic controller in departure and arrival phases, for example, delivery and reception of start-up, push-back, taxi clearance, routing information will be transmitted through data link and acknowledged by the pilots at traffic peak. This saves considerable time on radio communication and can avoid confusion or critical communication errors by intuitive text message and geographic symbol [12]. EMMA2 project found about 40% radio communication time was reduced when implementing traffic control through TAXI-CPDLC [22].

Several technologies exist such as VHF Data Link Mode 2 and Traffic Information System Broadcast (TIS-B) that could be used in the cockpit for higher-level A-SMGCS. Integrating with the Electronic Moving Map (EMM), flight crews can reference the assigned taxi route and surrounding traffic situation on the EMM. In EMMA2 project, pilots believed and were attracted by the designated taxi routes and the clearances showing on the EMM which were significant benefit for them as a guidance information [7].

2.7 Review of the Head-Up Display

An HUD is a projected display of symbols on a transparent glass 'combiner' screen where the symbols are superimposed over the pilot's forward field of view [23]. The HUD enables the pilot to monitor the performance and flight path guidance information while maintaining a view outside the cockpit [17]. As a result, the HUD provides the opportunity for more time to monitor the external domain instead of paying attention to the instrument status on the head-down display. The HUD was initially used for military gun sights not used as a flight instrument [24]. In 1960, the Hawker Siddeley Buccaneer was equipped with the first practical HUD designed for flight instrument [25]. This early HUD

contains some basic symbols, such as an airplane reference symbol, a horizontal line and the Flight Director designated basic guidance information. The commercial aviation HUD emerged in the early 1980's. The first commercial HUDs were installed by Air Inter on their MD-80 aircrafts [26]. These HUDs just replicated the guidance information on the Primary Flight Display. Afterwards, when the pilots found the HUD was more efficient to manage the high workload in approach and landing phases, the HUD gradually became an popular avionics in flight instruments and was installed in several commercial airplanes, such as Boeing 737NG, Boeing 787, Airbus A320 series, Airbus A350 and Airbus A380. The HUD currently has become the standard avionics in the cockpit of Boeing 787 [27]. The Figure 2-6 illustrates the HUD installed in the cockpit of Boeing 787.



Figure 2-6 The HUD in the cockpit of Boeing 787 [28].

2.7.1 Field-of-View Definition

The field-of-view of the HUD image is limited by the optics in the head-up display system. However, the optics are used to 'collimate' the HUD image in order to superimpose the essential navigational information and guidance geometries on the scene outside cockpit. There are four distinguishing Field-Of-View (FOV) characteristics for describing the angular region where the HUD image is represented to the pilots. The definitions of these four FOVs are defined in the SAE AS8055 'Minimum Performance Standard for Airborne

Head-Up Display (HUD)' standard [29]. Their relationship is illustrated in Figure 2-7 and summarized below:

Total FOV (TFOV) — The maximum angular extent where the symbology of the HUD image can be viewed by the both eyes when the pilot moves head vertically and horizontally within the HUD eye box.

Instantaneous FOV (IFOV) — The union of the two angular extents corresponding to each eye by the clear apertures of the HUD optics from a fixed head position within the HUD eye box. Therefore, the instantaneous FOV is composed of the view region of the left eye and the view region of the right eye from a fixed head position within the eye box.

Binocular Overlapping FOV — The intersection of the two angular extents corresponding to each eye from a fixed head position within the HUD eye box. The maximum angular extent viewed simultaneously by both eyes is defined by the binocular overlapping FOV.

Monocular FOV — The angular extent corresponding to one eye by the clear apertures of the HUD optics from a fixed head position. The size and shape of the monocular FOV may change according to the eye position within the HUD eye box.

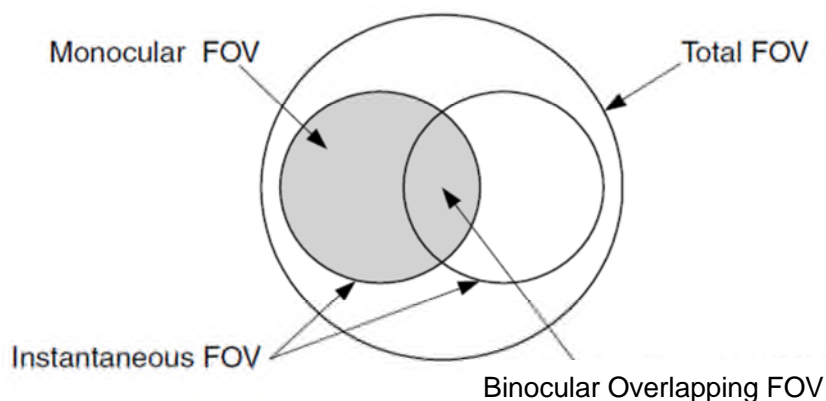


Figure 2-7 The HUD field-of-view defined [23].

2.7.2 HUD optical systems

There are two kinds of optical systems to collimate the HUD images, one is the refractive optical system, the other is the reflective optical system. The refractive optical system is similar to the military HUD optical systems developed in 1950's [30]. The optical system configuration is illustrated in Figure 2-8. The flat semi-transparent HUD combiner glass is designed to reflect approximately 25% of the collimated light from the Cathode-Ray Tube (CRT) and permeate approximately 70% of the real-world luminance. By adding a second flat combiner glass above and parallel with the first combiner glass, the vertical instantaneous FOV can be increased [23].

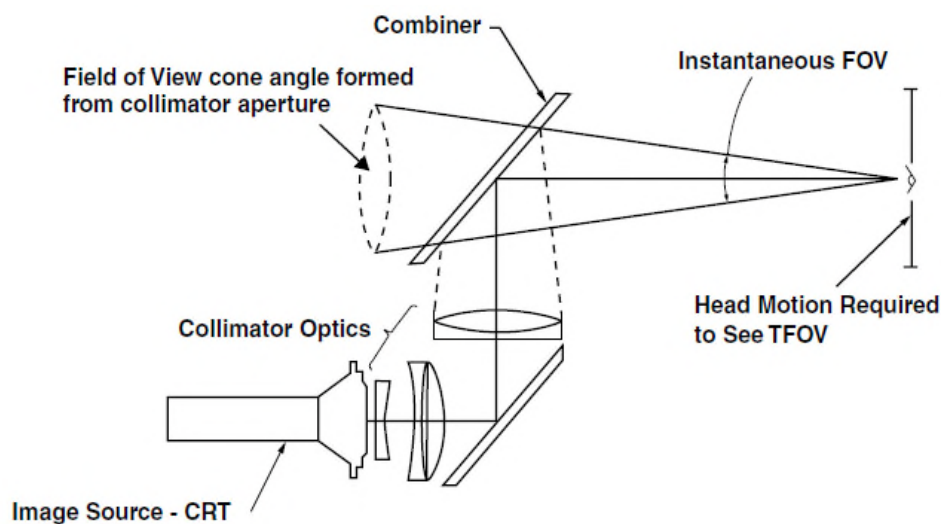


Figure 2-8 The refractive optical systems [23].

The reflective optical system was developed to obtain larger HUD field-of-view which may expand the use of the HUD and enable it to be a primary display device. The Figure 2-9 illustrates the reflective optical systems. The CRT is installed above the pilot in an Over Head Unit (OHU). The CRT image is transmitted through a relay lens assembly and reflected by a curved, transparent combiner. In order to avoid the pilot's head blocking the ray from the relay lens assembly, the combiner is designed in an off-axis angle. Compared to the refractive optical system, the reflective optical system can provide an IFOV and binocular overlapping FOV equal to the TFOV. This characteristic can

enable the pilot to see the whole of the image of the HUD with each eye without head movement.

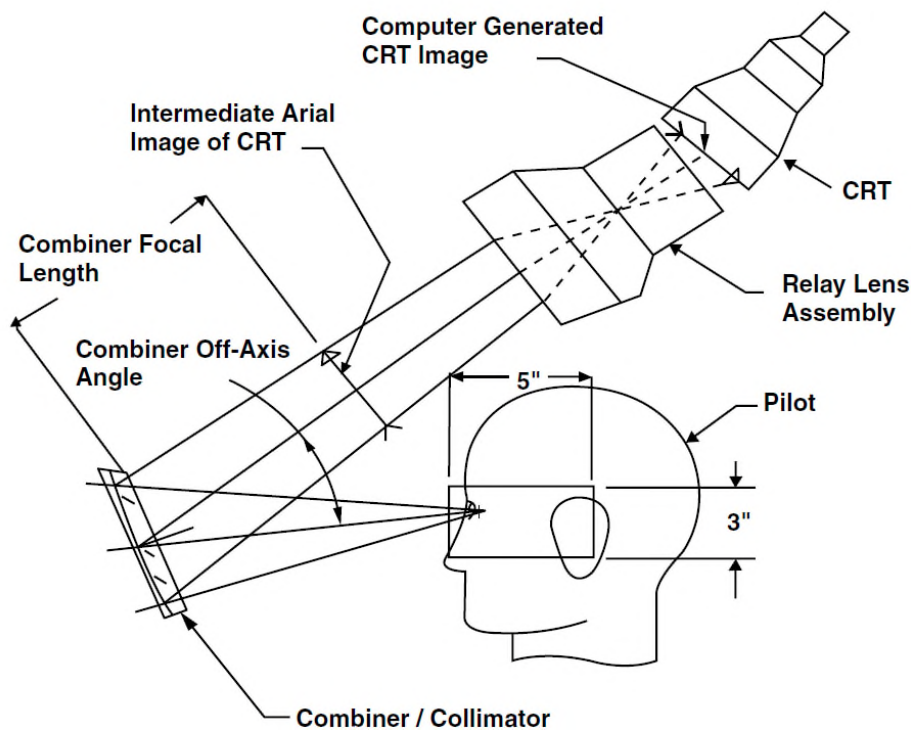


Figure 2-9 The reflective optical systems [23].

The comparison of the typical field-of-view performance characteristics for the refractive HUD systems and the reflective HUD systems is summarized in Table 2-1.

Table 2-1 Typical HUD Fields-Of-View [23]

	Refractive HUD FOV Characteristics ^a		Reflective HUD Optics FOV Characteristics
	Single Combiner	Dual Combiners	
Total Field Of View	20°–25° Diameter	25°–30° Diameter	22–28° V × 28–34° H
Instantaneous FOV	12° V × 17.8° H	16° V × 17.8° H	22–28° V × 28–34° H
Overlapping	11° V × 6° H	16° V × 6° H	22–26° V × 25–30° H
Monocular FOV	12° Diameter	16° V × 12° H	22–28° V × 30° H

^a Calculations assume a collimator exit aperture diameter of 5.0", and a distance of 24" between the pilot and the HUD collimator exit aperture.

This research will use the FOV of the reflective HUD to simulate the SGS, because all current commercial HUD systems in airline operation use the reflective optical systems [23].

2.7.3 HUD Symbols of Taxi

The HUD symbol sets used for taxi are similar to the symbol sets of rollout guidance as shown in Figure 2-10. During the rollout phase, the HGS provides the pilots with the calibrated guidance line to track the runway centreline and the digital countdown of the runway remaining. There are other symbols displayed on the HUD, such as the horizontal line with compass, the aircraft reference, roll scale and pointer, air speed and ground speed.

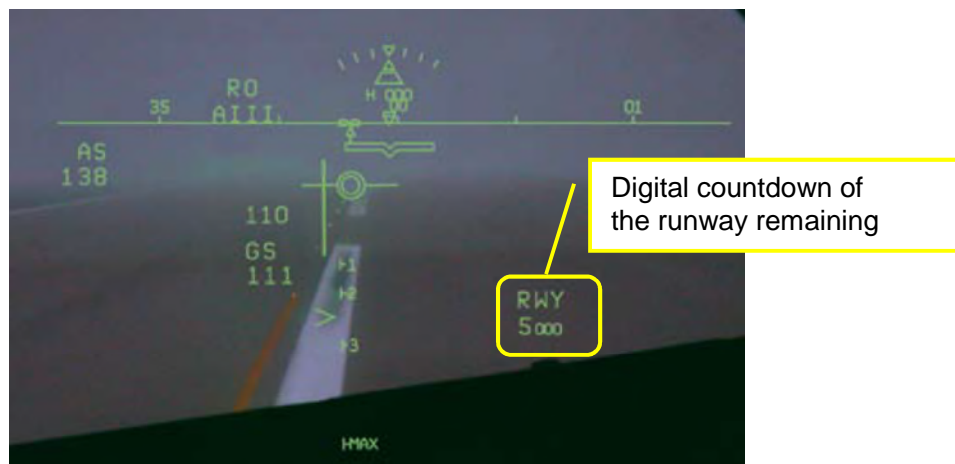


Figure 2-10 The rollout guidance symbols [31].

The aircraft reference symbol represents the projected centreline of the aircraft. The top centre point of the symbol is the actual centre point of the symbol, known as the Boresight.

The horizontal line, which is displayed associated with the aircraft reference symbol, is located according to the current aircraft pitch and roll attitude. The vertical distance between the horizontal line and the Boresight represents the pitch attitude. When the horizontal line is coincident with the Boresight, the pitch of the aircraft is zero degrees. The horizontal line represents the roll when it rolls left or right relative to the aircraft reference symbol. The horizontal line symbol is on a flat plane viewed from the pilot's eye.

The roll scale and pointer is located above the aircraft reference symbol with a scale which has tic marks for each 10° between 0° and $\pm 30^\circ$. The pointer points to the corresponding roll attitude on the scale.

2.7.4 HUD System Architecture

The basic HUD System architecture is illustrated in Figure 2-11. The HUD computer collects data from other instruments, such as the Inertial Reference System, Air Data Computer, radar altimeter, gyros, navigation radios and cockpit controls. Then, this data is transformed and transmitted to the HUD symbol generator to generate the x and y coordinates of the symbols. Finally, the symbols will be shown on the display unit to generate the HUD image.

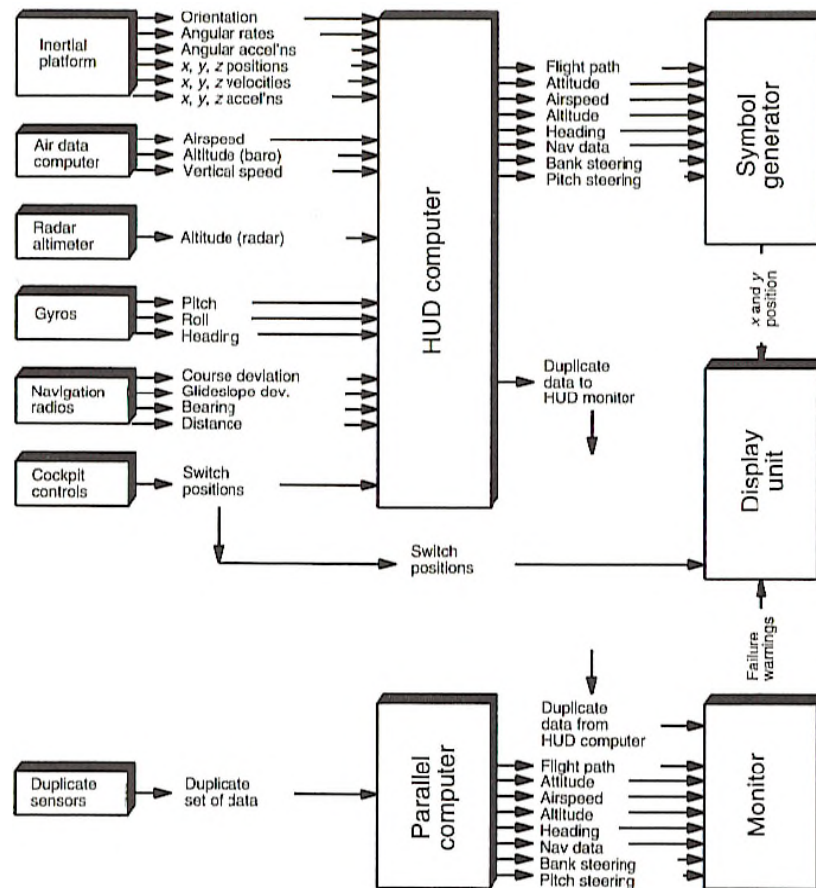


Figure 2-11 The basic HUD system architecture [24].

This basic architecture was used in this research. The HUD simulation block in the Simulink performed the function of HUD computer and Symbol generator in the HUD system architecture. The position and attitude of the airplane were

transmitted from the FlightGear simulator to the HUD simulation block in the Simulink to generate the symbol sets on the HUD. Java was used to program the display unit. The HUD symbols were displayed on a transparent screen generated by Java in the simulation.

3 METHODOLOGY

The research was mainly implemented in the simulation environment. The experiment data is collected from the simulation where several taxiing instances in FlightGear flight simulation were tested.

The following sequence is the general procedure for the simulation of the HUD surface guidance system. First, the simulation environment should be established because all the simulation of surface guidance information displayed on HUD simulation and IMM simulation is based on this simulation environment. Second, the cockpit simulator with HUD simulation and IMM simulation should be built to test the surface guidance system and the conflict warning information. Third, the pilots' tests need to be organized to improve the simulation of the surface guidance system.

FlightGear, Java, Simulink and Apache software were adopted to establish the simulation environment. FlightGear provided the cockpit of the own ship and the movement simulation of aircrafts on airdromes. As Simulink could obtain the built-in functions in Matlab which benefited accelerating simulation development and Java had an advantage on controlling the display system, Simulink and Java were used to create the surface guidance system which displays the guidance and warning information on HUD simulation and IMM simulation. Additionally, Apache software was introduced to communicate data between aircrafts and traffic controllers. The test pilots controlled the aircraft simulation taxiing on the taxiway by joystick. Compared to using Simulink to preset the aircraft movements, this control method provided a full control function to the pilots to taxi the aircraft on the airdrome. When taxiing on the airport, the surface guidance system obtained and converted the aircraft position information from FlightGear to generate the surface guidance information for the own ship and sent out the position information to the traffic controller. The traffic controller collected all the aircraft information on the airport and provided the guidance commands to the given aircraft. In the third step, in order to develop an efficient and intuitive system, the test pilots were invited to optimize the simulation of the surface guidance system.

3.1 Simulation Environment

3.1.1 FlightGear

FlightGear is a realistic flight simulator created by an international group of volunteers, and released as free, open-source GNU General Public License (GPL) software. It has been used for academic, research, and education. It has many technical document for further development, and a powerful Input and Output (I/O) system. This research will use the data communication between FlightGear and Simulink in order to obtain and tackle airplane orientation and location data from FlightGear and control and simulate the airplane movement in the FlightGear.

FlightGear supports numerous I/O protocol, such as, 'generic', 'garmin', 'joyclient', 'jsclient', 'native-ctrls', 'native-fdm', 'native-gui', native, 'nmea' and 'httpd', etc. Although there are some differences among these I/O protocol, they can be operated simultaneously when using them to communicate with FlightGear. There is a protocol named 'httpd' which can be used to access FlightGear property tree on web browser. After designating the 'httpd' options in FlightGear setting options, FlightGear will create a http server under the specified port designated in the setting options. Nearly all the property data in FlightGear can be accessed through this 'httpd' protocol, as well as displayed on the web browser in address `http://localhost:port`.

Property tree in FlightGear is generally considered as an important puissant system, because it provides access to low level run time state variables via a very intuitive tree-like hierarchy and this character is a benefit for facilitating control and manipulation at run time. The property tree contains most of the internal state of all systems within FlightGear, for example, the flight dynamics model, orientation, position, instrumentation and environment in FlightGear. The values of these internal states are presented in a hierarchically manner and can be accessed through I/O protocol.

3.1.2 Generate Cranfield Airport in FlightGear

The accurate airport model should be introduced to the project. Ordnance Survey can provide an accurate map of Cranfield Airport in AutoCAD format. There is an intersection area crossed by two taxiways and one runway. The guidance control in this area may be very complicated when taxiing back from the runway to the aprons. The taxiway connected with the aprons is not straight, the edges of the taxiway are formed by curves. The guidance information may become complicated as a result of these curves. Considering the complexity of surface movement and the accuracy of the taxiway geometries, Cranfield airport is chosen as the airport in the simulation environment.

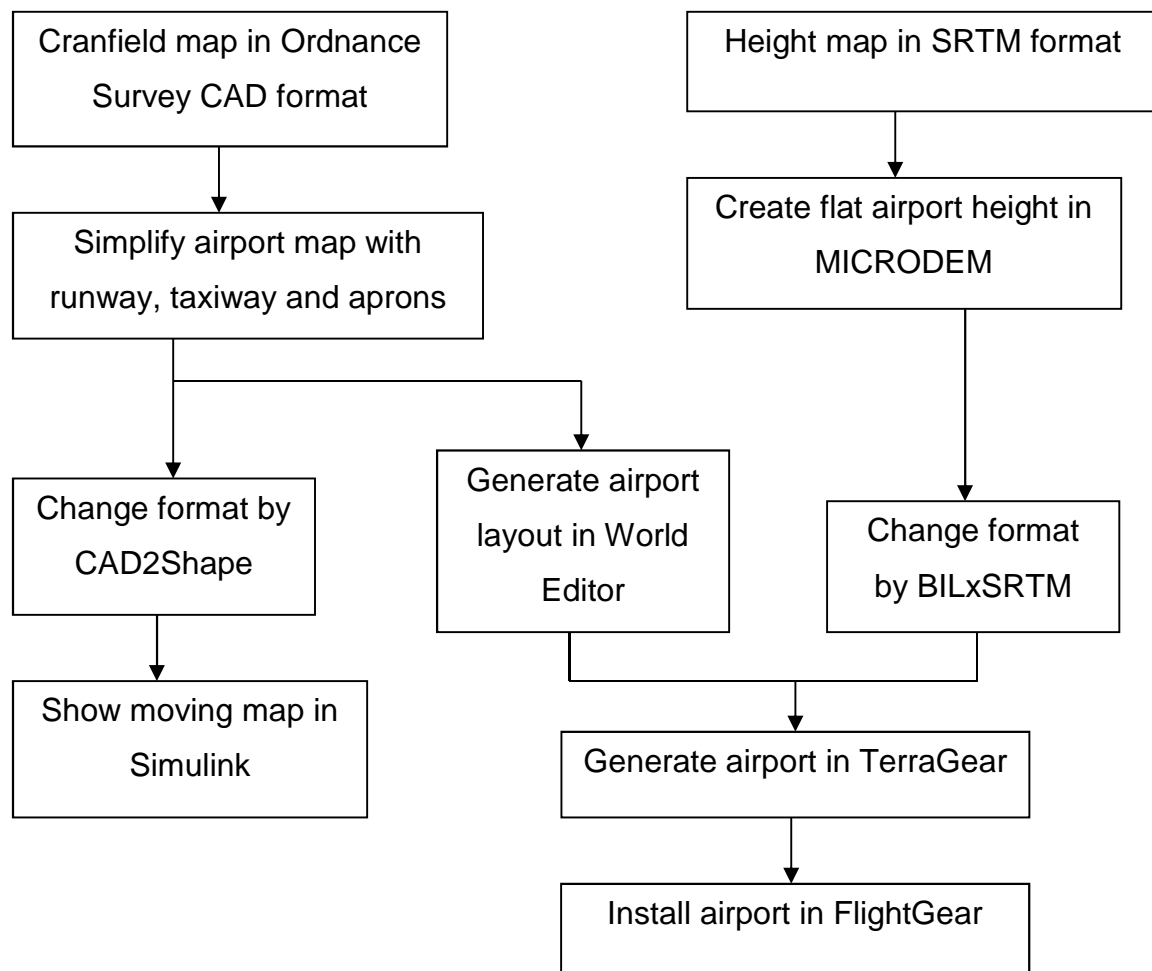


Figure 3-1 Data processing to generate the airport

One of the simulation scenarios is taxiing on the taxiway of Cranfield airport in departure or arrival phase. But because there are no existing Cranfield airport

scenery in FlightGear, a Cranfield airport scenery has to be build and installed. In order to generate an accurate simulation environment, data from Ordnance Survey was used. One of the data processing procedures to generate the airport is shown in Figure 3-1. Because the Ordnance Survey data is convenient to obtain and it can be transformed to the WGS84 coordinate system which is used in FlightGear, the Ordnance Survey map is chosen as the data base of the simulation environment. Other accurate airport geography data can also be used for establishing the simulation environment if they can be transformed to the WGS84 coordinate system.

The Ordnance Survey data is a CAD file of a map with the airport taxiway, runway, buildings in Cranfield University and Cranfield village, and presented in National Grid which is used on all Ordnance Survey maps. The map is simplified to display runway, taxiway, aprons in order to save calculation capacity in the following processing.

In Great Britain, Ordnance Survey coordinates relate to OSGB36 National Grid which has been accepted as a national standard. OSGB36 National Grid coordinate system uses the Airy 1830 ellipsoid, which is designed to best-fit Britain only, for mapping in Britain [32]. The airport map from Ordnance Survey provides the easting and northing which are known as the plane coordinates, grid coordinates or map coordinates. These coordinates are used to locate position with regard to the Ordnance Survey airport map, which is a two-dimensional plane surface portraying sceneries on the curved surface of the earth. Easting and northing are the two axes of the map coordinates which adopt an ordinary two-dimensional Cartesian system. The map coordinates of a point on the Ordnance Survey airport map are calculated from the ellipsoidal latitude and longitude by a standard formula known as a map projection which is relative with a projection of Transverse Mercator type called Ordnance Survey National Grid. Ordnance Survey has provided the formulae for the Transverse Mercator projection in the guidance of coordinate systems in Great Britain.

However, FlightGear follows the modern trend and uses the GRS80 ellipsoid which is used in the WGS84 coordinate system everywhere on account of global compatibility. WGS84 coordinate system is the global geodetic reference system used to describe the position of GPS satellites and ground stations. World Editor uses the Transverse Mercator projection to generate a 2-D airport layout with the latitude and longitude in the WGS84 coordinate system to locate the positions of points on the airport. As the original data is the easting and northing reading from the map, a method to transfer the easting and northing on the Ordnance Survey map to the latitude and longitude in the World Editor has to be performed before generating the layout of the airport by World Editor.

Easting and northing are in the OSGB36 National Grid coordinate system, while latitude and longitude are in the WGS84 coordinate system. But there is no direct transformation method after several researches, Ordnance Survey simply has provided the transformation method from OSGB36 National Grid coordinate system to transfer to ETRS89 coordinate system. The first step is computing the ETRS89 easting and northing from OSGB36 coordinates, then, calculating the ETRS89 latitude and longitude. The relationship between ETRS89 coordinate system and WGS84 coordinate system has to be defined. In Europe, ETRS89 is a precise version of the better known WGS84 reference system optimised for use in Europe. However, for most purposes it can be considered equivalent to WGS84. Ordnance Survey suggests the term ETRS89 should be taken as synonymous with WGS84 for all navigation, mapping, GIS, and engineering applications within the technically stable parts of Europe [32]. This transformation method for one point is not efficient when transforming all the points on the airport map, because there are nearly 5 thousand points on the airport map. A calculation tool called Grid InQuest (Version 7.0.0 Build 4737) published by Ordnance Survey in 2013 is introduced to transform a batch coordinates of points recorded in Excel files.

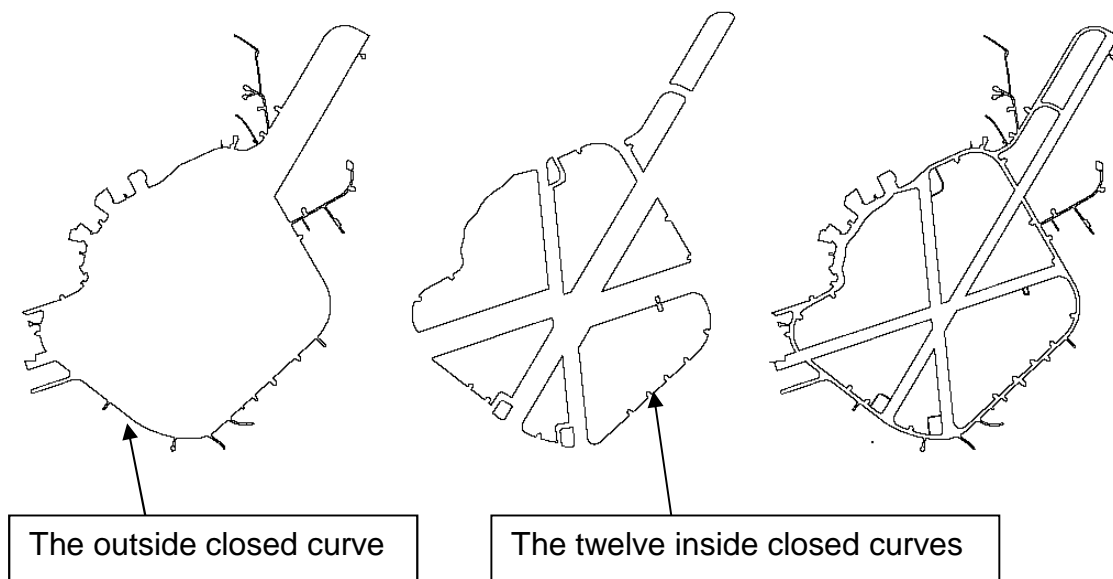


Figure 3-2 Taxiway closed curves connecting strategy

In order to obtain all the map coordinates on the simplified Ordnance Survey airport map and to depict these coordinates in the World Editor to generate the layout of the airport, the following procedure is performed.

First, connect a plurality of adjacent points of taxiway edges to become the closed curves in AutoCAD and save these curves respectively into original AutoCAD files with DWG suffix. Because of the limitation in World Editor, the taxiways have to be described by superposing several curves when drawing taxiways. Figure 3-2 illustrates the connecting strategy for the closed curves. The outside closed curve on the left of Figure 3-2 is the outside edges of all the taxiways on the airport map, this curve generates the outside edge area of the airport taxiways. On the centre of Figure 3-2, there are other twelve inside closed curves which are the other edges of the taxiways, but these curves are generated like holes in the airport field. Thus, the taxiways are obtained by subtracting the inside hole areas from the outside edge area.

Second, introduce CAD2Shape to transform the AutoCAD files of curves into Shape files, which can be read by Matlab. Third, use Matlab to read the Shape files with the function 'shaperead' and replicate the results of map coordinates to the Excel files. Fourth, utilize the batch transformation function of Grid InQuest to read and transform the map coordinates in the Excel files to latitude

and longitude coordinates. The transformation results which are latitude and longitude coordinates of all the points on the Ordnance Survey map are saved in new Excel files.

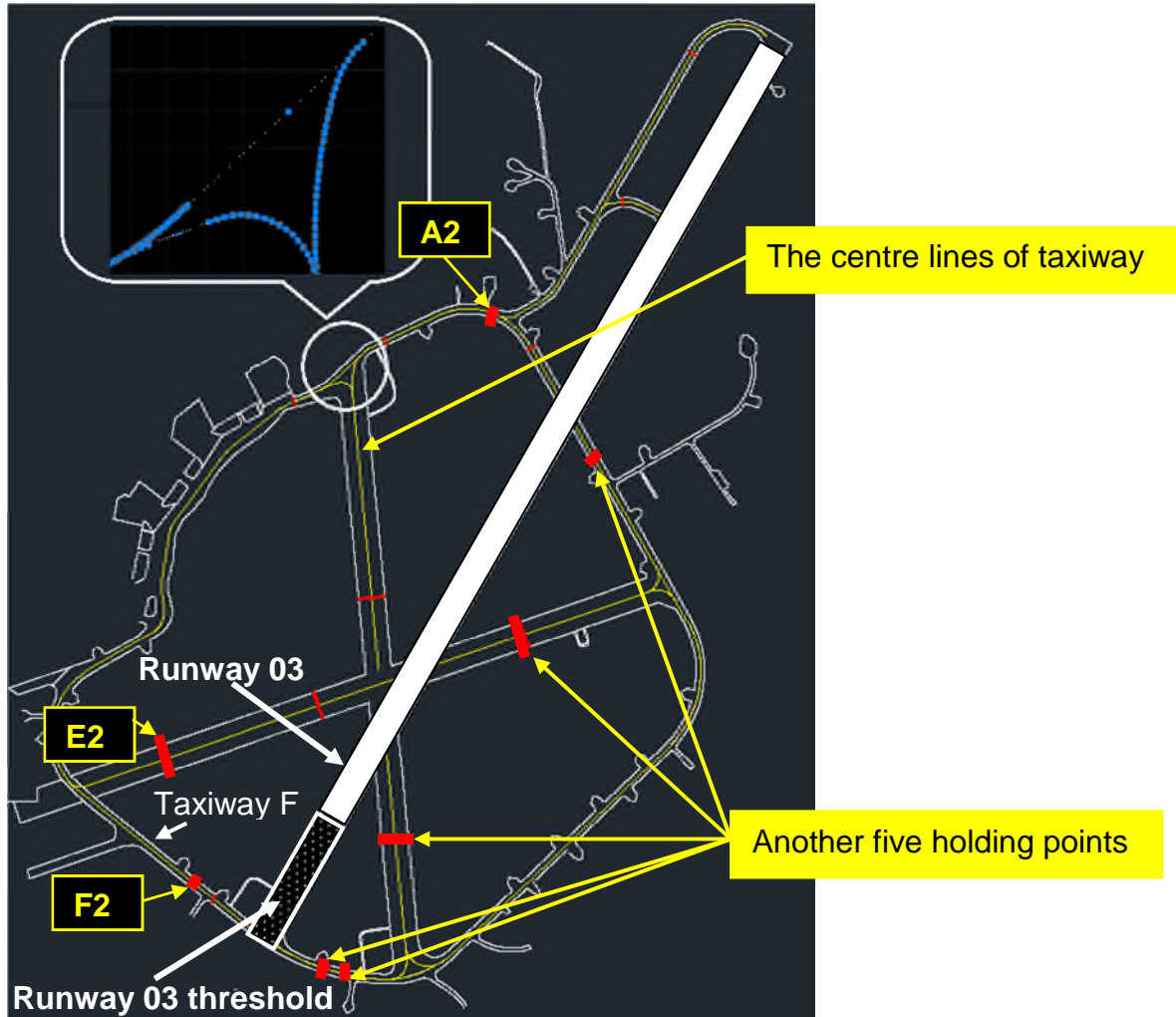


Figure 3-3 The airport symbols

Because there is no automatic import function to insert the latitude and longitude coordinates into World Editor, the latitude and longitude coordinates of each point on airport map will be replicated manually to World-Editor to create the layout of airport including the taxiway, runway and apron. However, the centre line of taxiway is not included in the Ordnance Survey map; measurement for latitude and longitude coordinates of the centre line on the real airport or drawing the centre lines of taxiways on the Ordnance Survey map may be performed by referring to the Google map. Considering the project lead

time and GPS accuracy on Google map, drawing the centre lines of taxiways by referring to the Google map was chosen for the project. The centre lines are the database of an airport map, and will be used for generating guidance lines in the surface guidance system. The centre lines are composed by lines and curves, but curves cannot be depicted accurately in World Editor by just inserting several controlling points manually. One of the accurate approaches is to use the polylines to approximate the curves. The endpoints of polylines segments should be on the corresponding curve lines. As a result, the 'divide' command in AutoCAD is used to divide the curve lines into equidistant lines and generate a series of points on the curve lines. In Figure 3-3, the yellow curves are the centre lines of taxiway and the blue points are the serial points used for drawing centre lines in World Editor. Because the polylines are used to approximate the curves in World Editor, there are a series of points which define the two endpoints of each polylines segments on the curves. However, simple straight lines just need two endpoints to define it and there are parts of the centre lines that are straight lines; that is why there are some segments of curves just using two endpoints to approximate. Because the centre lines cannot be described by one consecutive curve, the centre lines have to be divided into twelve curves in order to depict them separately in World Editor. The division strategy is illustrated in Figure 3-4, the longest blue centre line is like the trunk and other black centre lines are similar to the branches. Considering the accuracy of centre lines and the complexity of generating the centre lines in World Editor, the distance between the two adjacent points on centre lines is set to about one meter. After performing the above map coordinates transformation procedure, the latitude and longitude coordinates can be saved in Excel files and replicated into World Editor to generate the centre lines of taxiways.

Although the holding points are not depicted on the Ordnance Survey map, they also need to be drawn by referring to Google map and generated according to the above procedure. The symbols of holding points are depicted according the ICAO airdrome chart, Licensing of Aerodromes and Aeronautical Information Manual [33, 34, 35]. There are eleven holding points illustrated on the ICAO

chart of EGTC, but in order to obtain more complicated test scenarios, as illustrated in the Figure 3-3, another five holding points are added on the taxiways which are located on the right side of runway 03. As these holding points are always the destinations of surface guidance which are designated by the traffic controllers, they are depicted in red colour on the Ordnance Survey map in order to highlight their positions.

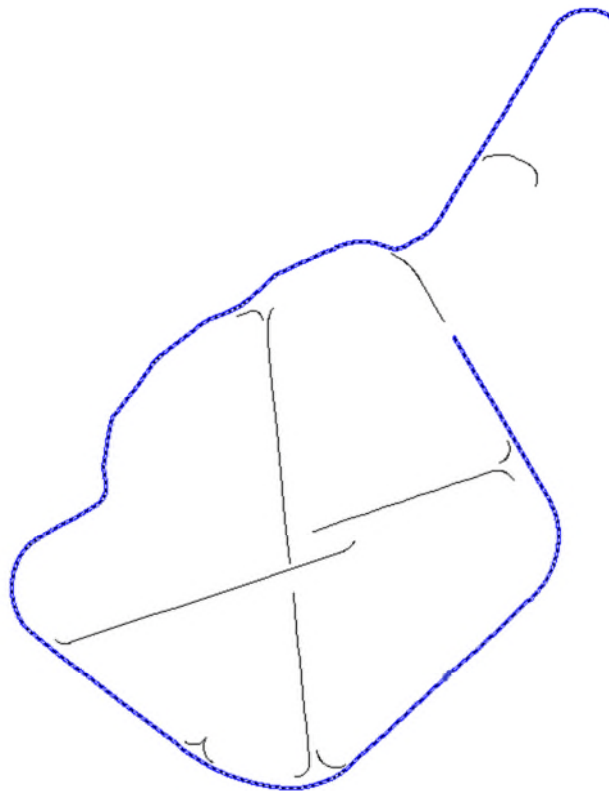


Figure 3-4 The division strategy of the centre lines

Normally, the World Editor uses the airport satellite picture as the drawing template, as depicted in Figure 3-5, aircraft model developers find the points on the edge of the taxiway on the satellite picture using the mouse manually. This approach cannot guarantee the accuracy of the GPS position of the taxiway because it is not convenient to obtain an accurate satellite picture of the airport. However, an ordnance survey map provides the accurate coordinates of a series of points on the edge of the taxiway, and it is possible to use these

accurate coordinates to draw the taxiway in World Editor. As mentioned before, the thirteen closed curves are used to depict the taxiway. They have to be defined successively in World Editor. The outside edge of the taxiway as the first curve should be defined initially, then, the other twelve curves are defined to subtract the area surrounded by the first curve.



Figure 3-5 Drawing the taxiway using the satellite pictures [36]

There are mainly three main functional blocks on the interface of World Editor. As shown in Figure 3-6, the left functional block is the drawing area which displays the layout of the airport. The functional block in upper right corner is the feature list of all the features such as runway, taxiway, centre lines on the layout. The last functional block is in the lower right corner, when one of the features in the feature list is selected; it controls all the detail information of the features such as the latitude and longitude of the points.

The procedure of defining the closed curves in World Editor is as follows. First, choose the 'Taxiway' function and draw the points randomly in the drawing area. The quantity of points should be the same with the points on the closed curves. Second, modify the longitude and latitude of the above points successively according to the transformation results of the map coordinates of the closed

curves. These points are called vertices, while the curves are called Polygon in World Editor. If the 'Select Vertices' function is triggered, the vertices of the feature will be selected in light green colour, then the detail information of these vertices, such as latitude and longitude coordinates, will be displayed in the lower right functional block. If the 'Select Polygon' function is triggered, the polygon of the feature will be selected in orange colour and the attributes of the feature, such as the surface material, visibility of the feature, line attributes and light attributes, can be modified in the lower right functional block. The surface material of the taxiway is set to concrete as the real airport by triggering the 'Select Polygon' function.

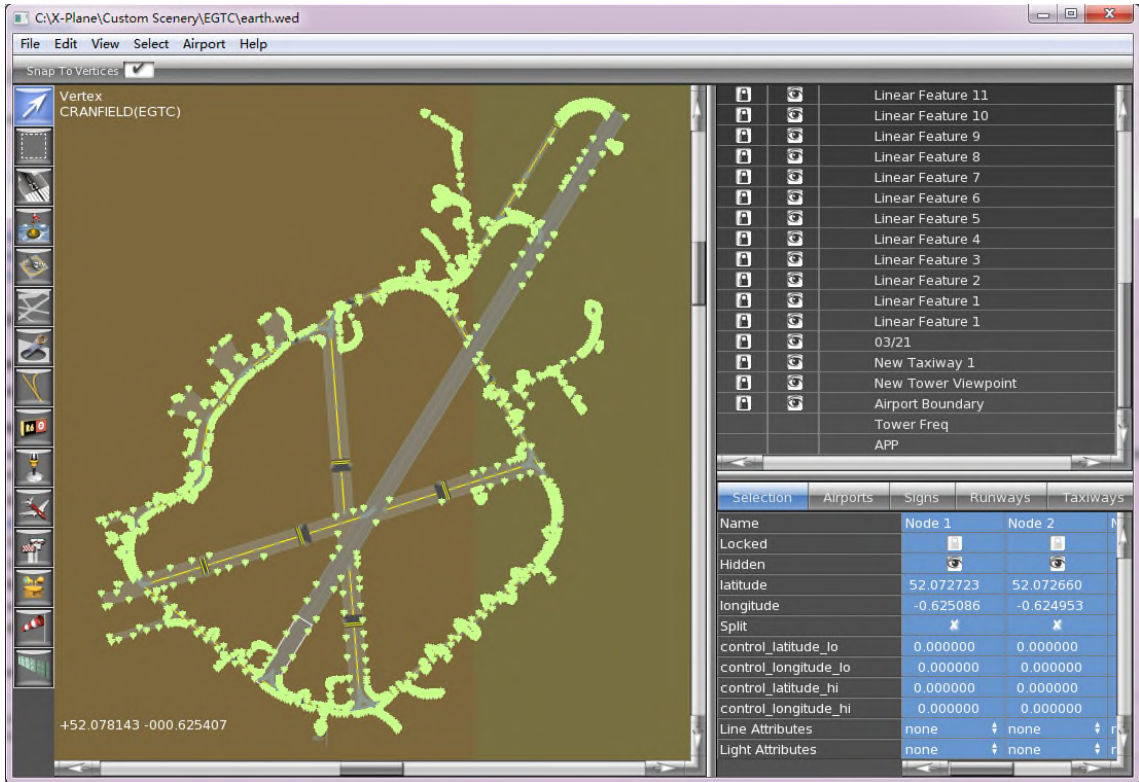


Figure 3-6 The serial points to define the taxiway

Figure 3-6 shows all the light green points defined in World Editor to generate the taxiways. There are 2,962 points defined by latitude and longitude on the airport layout to generate the taxiways. Because of the complexity of shape, the curve of outside edge of taxiways has 1781 points on the Ordnance Survey map. Over half of the total quantity of the points on the taxiway edges are used to define the outside edge of the taxiways.

Not only the taxiway be defined on the airport layout, but also the runway should be depicted. The latitude and longitude of the end points of the runway is used to locate the runway in World Editor. Their coordinates are listed on the ICAO airdrome chart. Although the two end points fix the length of the runway, the width which can be queried from the ICAO chart should also be defined in the layout. The Runway 03 threshold should be drawn on the layout, otherwise, the taxiway F will not be connected with the Runway 03. The length of the threshold can be obtained from the ICAO chart. After triggering the 'Select Polygon' function, the surface material of the runway can be set to the asphalt according to the ICAO chart.

The next important feature is the centre lines of taxiways which will be used to guide the surface movement. Although the centre lines of taxiways are not closed curves, the procedure of defining the polylines of centre lines in World Editor is similar to the closed curves. The Linear Feature in World Editor is used to define the polylines. First, choose the 'Taxilines' function to depict the Linear Feature and draw the points randomly in the drawing area by clicking the mouse. The quantity of points should be the same with the points on the polylines. Second, modify the longitude and latitude of the above points successively according to the transformation results of the map coordinates of the polylines. There are 1216 points used to define the centre lines, 796 points among them are used to define the trunk of the centre lines, while others are used to define the branches. The 'Line Attributes' of the centre lines are modified to solid yellow line and the 'Light Attributes' of the centre lines are modified to green Taxiway Centreline Lights.

The last features of airport layout are the holding points. They are also depicted by Linear Feature. Compared to the centre lines approximated by polylines, the holding point is more simply described by a line segment. The latitudes and longitudes of the end points of the line segment are transformed from the map coordinates of holding points by implementing the procedure of coordinate transformation provided by Ordnance Survey. According to the ICAO chart, there are two kinds of 'Light Attributes' of the holding points, one is called 'ILS

Hold', the other is called 'Runway Hold (Black)' in World Editor. As shown in the Figure 3-3, the holding point A2, E2 and F2 are depicted with 'ILS Hold' symbol, while other holding points are depicted with 'Runway Hold (Black)' symbol.

After performing the above procedures, the layout of the airport can be created in World Editor. However, the World Editor software only generates the airport layout within a file suffixed with 'dat'; the airport will not be displayed in FlightGear without terrain data of the airport. The height maps for the area around the airport will be used to create the terrain data of airport through a scenery generator called TerraGear.

The height maps are Shuttle Radar Topography Mission (SRTM) files which contain the elevation data above sea level around Cranfield airport. NASA has released version 2 of the Shuttle Radar Topography Mission digital topographic data, and the data may be obtained through this URL: <http://dds.cr.usgs.gov/srtm/> provided on NASA Jet Propulsion Laboratory website. All SRTM data are divided into tiles extending over 1° x 1° of latitude and longitude, in “geographic” projection. As the location of Cranfield airport shown on the aerodrome chart proved by ICAO is at 52°4'20"N 0°37'0"W, the SRTM files of two tiles (N51W001.hgt and N52W001.hgt) where the airport is located are chosen to generate the airport scenery.

The height maps is used to cover the sea level surface of FlightGear environment to generate the terrain scenery after being treated by TerraGear. In order to obtain an accurate airport model in FlightGear to simulate the taxiing scenarios, the GPS position of the airport model has to be checked to ascertain whether it is the same as real world. After several researches by checking the GPS position of aircraft which is located on the sea level surface in FlightGear, it is obvious that the shape of the sea level surface in FlightGear is the same with the WGS84 ellipsoid. Thus, it is necessary to verify whether the sea level surface in Britain is the same as the shape of WGS84 ellipsoid. If they are same, the height maps can be used directly. But if they are different, the height maps have to be adjusted in order to obtain the same GPS position in FlightGear as the real world.

Latitude and longitude locate a position on the surface of the WGS84 ellipsoid, but real points on the airport are actually above the ellipsoid surface, the item 'ellipsoid height' is introduced to depict the GPS position of the points. Ordnance Survey states that the ellipsoid height is the length of a vertical straight line segment from the point to the ellipsoid surface. As stated on the ICAO chart, there are two kinds of height recorded for the specific points on the airport, such as the end points of the runway. One is the Geoid Undulation (GUND), and the other is the mean sea level height (ELEVATION IN FEET AMSL). The Geoid Undulation is the height of the Geoid (mean sea level) above the Reference Ellipsoid (WGS84) at the stated position. The relationship between the ellipsoid height H and the mean sea level height h is shown in equation 3-1.

$$H = h + N \quad (3-1)$$

the item N is the Geoid Undulation. Figure 3-7 shows mean sea level height compared to ellipsoid heights. The dotted mean sea level continued under the land is actually a local geoid model. According to the ICAO chart, the airdrome elevation is 358 feet and the GUND Elevation is 154 feet. So, the ellipsoid height of the airdrome is 512 feet.

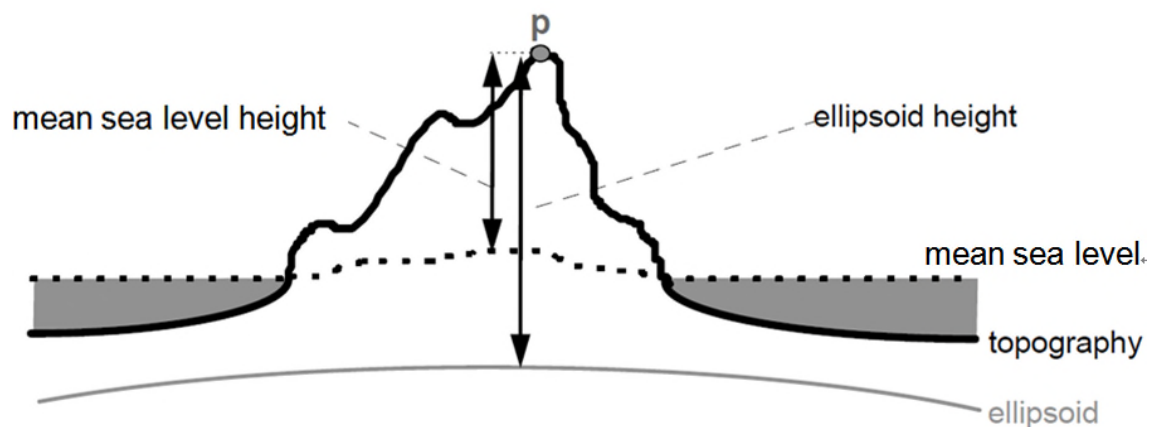


Figure 3-7 A simply representation of the mean sea level height [32]

Because the GUND Elevation is not equal to zero, the mean sea level surface is not the same with the ellipsoid surface in the real world as shown in Figure 3-7. However, as mentioned before, the mean sea level surface in FlightGear is

equivalent to the WGS84 ellipsoid. So, it is obvious that the ellipsoid height is equivalent to the mean sea level height in FlightGear environment. Thus, after adjusting the height maps to the correct mean sea level height, the right ellipsoid height of the airport can be obtained. Because the ellipsoid height of the airdrome in the real world is 512 feet, the mean sea level height of the airdrome area on the height maps has to be adjusted to the same value.

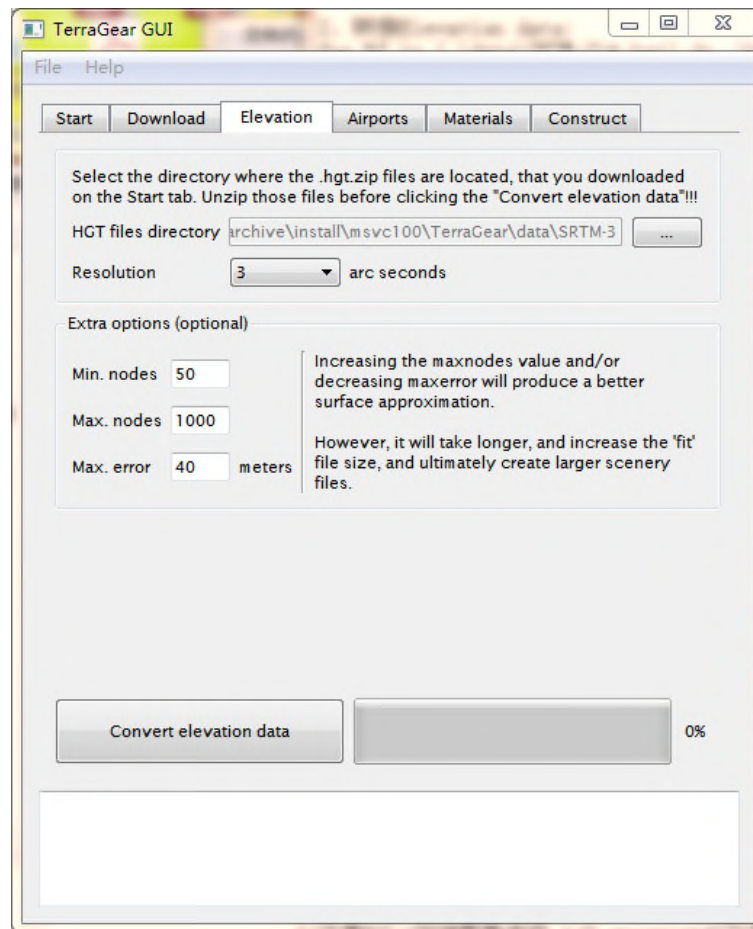


Figure 3-8 Convert elevation data.

MICRODEM is a free software for mapping program written by Professor Peter Guth of the Oceanography Department, U.S. Naval Academy. It displays and merges digital elevation models, satellite imagery, scanned maps, vector map data and Geographic Information System (GIS) databases. MICRODEM is introduced to adjust the terrain scenery of the airport to the accurate mean sea level height in FlightGear. When opening the above SRTM files in MICRODEM, the surface around the airport is not flat. In this research, MICRODEM is used

to display and modify the SRTM files (the height maps) in order to obtain a flat airport surface with a command to set a height range around the airport to a constant. But MICRODEM cannot save the modified height maps to SRTM format, so another software named BILxSRTM was used to convert BIL format files generated by MICRODEM to SRTM format files.

With the modified SRTM files of flat surface around airport and airport layout files generate in World Editor, a software called TerraGear and its Graphical User Interface (TerraGear GUI) are used to generate the airport scenery. The steps are as follows. First, select the directory of HGT files which are SRTM format files modified in MICRODEM as shown in Figure 3-8, then press the button "convert elevation data" to change the SRTM files to the format which TerraGear can used to generate the scenery. Second, select the directory of DAT file which is the layout of airport generated in World Editor as shown in Figure 3-9, choose the correct data format to 850 and select the Single airport with Cranfield airport ICAO code as EGTC, then press the button "generate airport" to create the scenery of the airport. Two folders (AirportArea and AirportObj) within the files of airport scenery will be generated in the work directory of TerraGear. These two folders recognised as downloaded scenery need to be replicated to the installation directory of FlightGear.

Another function called TerraSync has to be set in FlightGear to integrate the new airport scenery to FlightGear. TerraSync is responsible for synchronizing the FlightGear Scenery Database with the downloaded scenery. After setting the TerraSync directory and manually refreshing the airport index in the FlightGear, the airport scenery can be shown in FlightGear simulation environment.

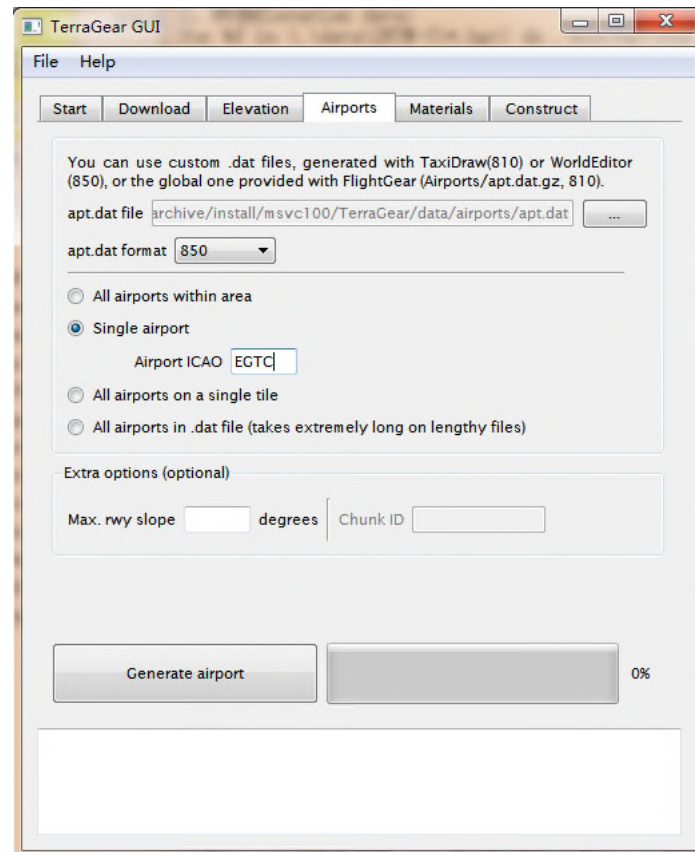


Figure 3-9 Generate airport.

3.2 Head Down Display System

3.2.1 Shape Files of Airport

The moving map displayed on the head-down display system is used to enhance a pilot's situation awareness. A moving map of Cranfield airport is generated in MATLAB and Simulink environment to show the position and orientation of airplane.

Cranfield map produced by Ordnance Survey is used in this research. The map is in AUTOCAD format drawing in National Grid coordinates, but the AUTOCAD format cannot be read directly by MATLAB. The shape files can be directly read and operate in MATLAB through a function called 'shaperead'. And one software named CAD2shape shown in Figure 3-10 enables to convert the AUTOCAD file to shape file.

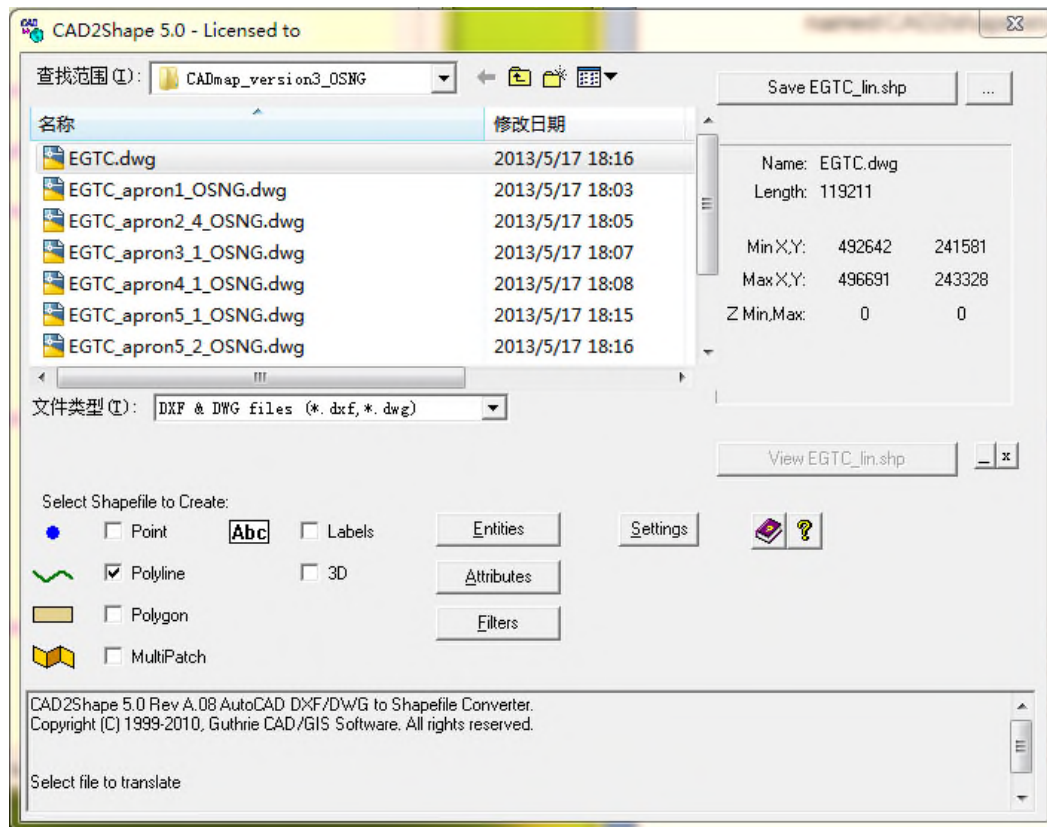


Figure 3-10 CAD2shape interface

Considering the different colour of element in airports, such as yellow centre line, white taxiway and runway, red holding point marking, and grey aprons, the AUTOCAD map is separated into several maps, such as the map of taxiway and runway, taxiway centre line, holding point markings and aprons, for manipulations in MATLAB. As described in the coordinate transformation procedure to generate the airport model, one of these manipulations is to obtain the map coordinates of points on the map. After setting the conversion options in CAD2shape, the Geometry and ID features which are useful to generate the moving map will be saved as polygon in the shape files, while other attributes in the AUTOCAD maps, such as layer, colour, width of line will be abandoned, as some of these abandoned attributes need to be adjusted in MATLAB in order to distinguish the centre lines of taxiway, taxiways, runways and aprons displayed on the IMM simulation. For example, the centre lines of taxiway will be displayed in yellow, while the taxiways will be depicted in white and the aprons will be shown in blue.

The shape files will be displayed in figures of MATLAB to simulate the airport map displayed on head-down display using the function 'plot' for taxiway, runway, centre line of taxiway, holding point marking and function 'fill' for aprons. The input parameters of these two function are matrices, however, the function 'shaperead' just returns the geographic data structure array which combines geometric and feature attribute information of the shape files. Therefore, another function called 'rmfield' is used to remove the specified field from the structure array returned from 'shaperead' function and obtain the matrices of all geometric information in the geographic data structure. After the disposal of function 'shaperead' and 'rmfield', the plot and fill can be used to draw the map in a default figure and axes.

In order to achieve the simulation of moving map, the syntax for creating figure and axes is introduced to define the figure and axes. The syntax `h = figure('PropertyName', propertyvalue,...)` enables a new figure graphics object using the values of the properties specified to be created and returns the handle (h) to the figure object. The property of 'Name', 'FileName', 'Units', 'Position' and 'Color' is specified to define the figure with black background.

If the graphic airport map needs to be drawn on figure, the axes where the map is located has to be specified. Similar to the syntax of figure, the axes is manipulated and specified by its properties. The handle of the figure is defined as the parent property of axes, and 'Visible' property is set to 'off' in order to hide the visibility of the axes, otherwise, another axes for the fixed airplane symbol will be covered by this axes for the airport map when the axes is rotating to simulate the moving map.

The aircraft symbol fixed on the figure is also shown on the airport map to indicate the location of the airplane. This symbol is drawn in another axes to distinct with the axes of airport map, because the axes of the fixed airplane symbol need to be immobile.

3.2.2 Simulink Structure for Moving Map

With the above operation, the shape files can be displayed on the figure, but cannot move and rotate according to the position and orientation of an airplane. As a simulation environment, all the aircraft position and orientation data is generated in the FlightGear and transmitted to the Simulink to drive the moving map and head up guidance information. Figure 3-11 shows the high level architecture of the guidance simulation.

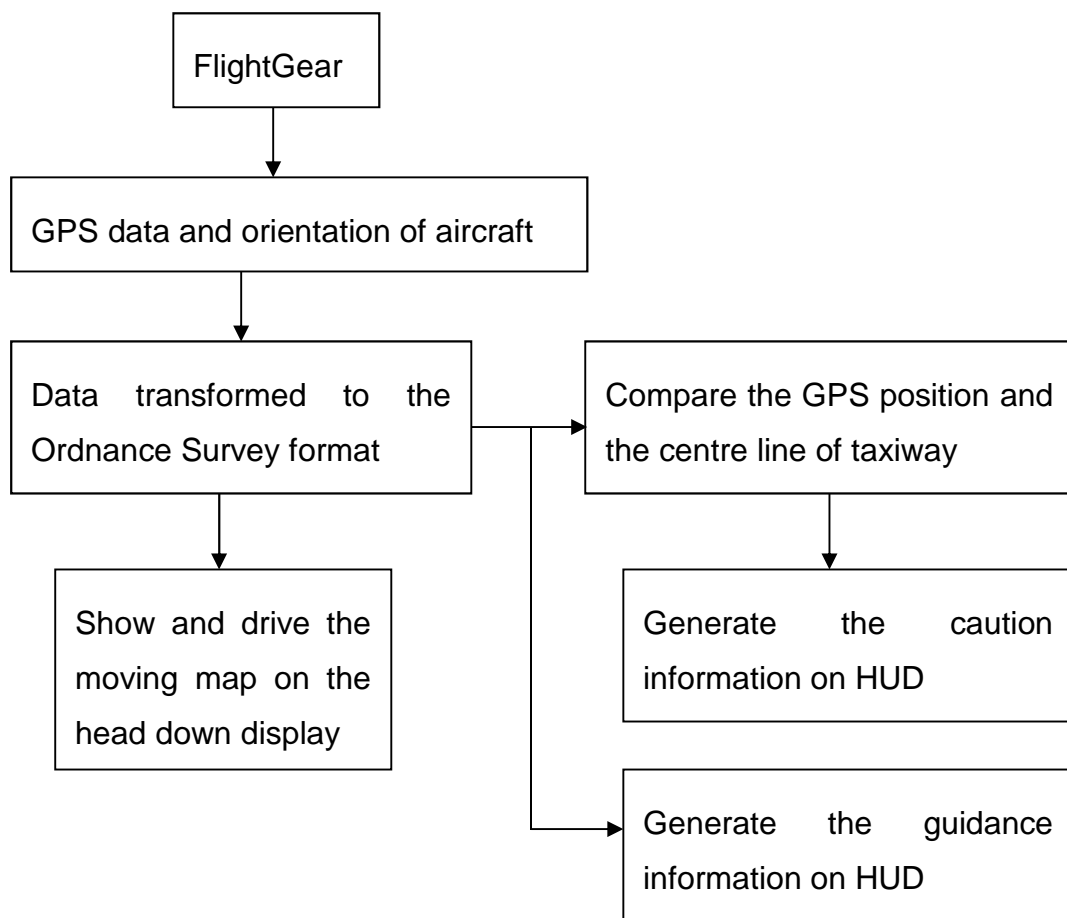


Figure 3-11 architecture of the guidance simulation

In order to achieve the target of moving the airport map, several blocks in Simulink are developed using Level-2 MATLAB S-Functions.

The simplified Simulink structure with S-Functions blocks is illustrated in Figure 3-12. The detailed Simulink structure is illustrated in Appendix A.

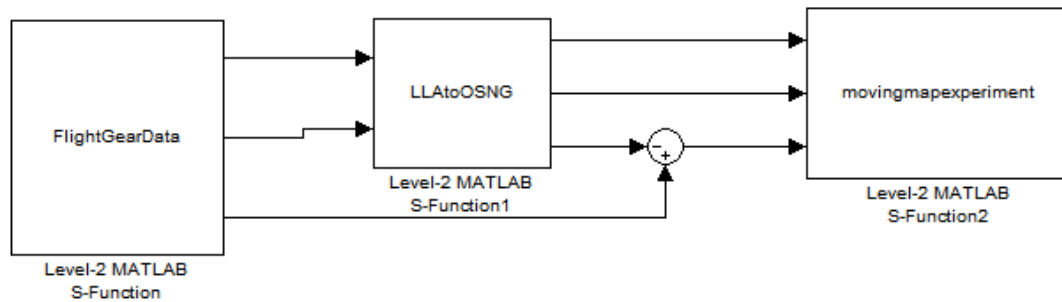


Figure 3-12 Simulink structure of moving map

There are three blocks developed with Level-2 MATLAB S-Function and one block introduced from the blocks library in Simulink.

The first block named FlightGearData enables Simulink to catch the data from FlightGear when an aircraft is taxiing on the airport by accessing the appropriate data such as Latitude, Longitude, and heading of the airplane in the property tree of FlightGear. The function 'java.net.URL' is introduced to access the property tree in the host of FlightGear. With the help of text filter functions in MATLAB, the pure latitude, longitude and heading data can be obtained from the property tree. The output signals of the FlightGearData block are Latitude, Longitude and heading of the airplane taxiing on the airport.

The second block named LLAtOSNG enables Simulink to transfer the position data from Latitude and Longitude in World Geodetic System 1984 (WGS84) to the Easting and Northing coordinate in National Grid coordinate system which is used by Ordnance Survey for mapping Great Britain. The transformation is calculated with reference to the Transformations and OSGM02 user guide published by Ordnance Survey [37].

GPS enables the location on the Earth's surface to be defined via geographical coordinates of latitude and longitude. Graticule which is like a framework is formed by the parallels and meridians which represent the values of latitude and longitude. The graticule covering Great Britain is shown in Figure 3-13. If airports on the curved surface of the earth are represented on a flat surface by means of map projections, their shape will always be influenced by distortion. In

order to limit the unavoidable distortions, Ordnance Survey designed a particular type of map projection called the Transverse Mercator projection to present maps on a flat surface with National Grid.

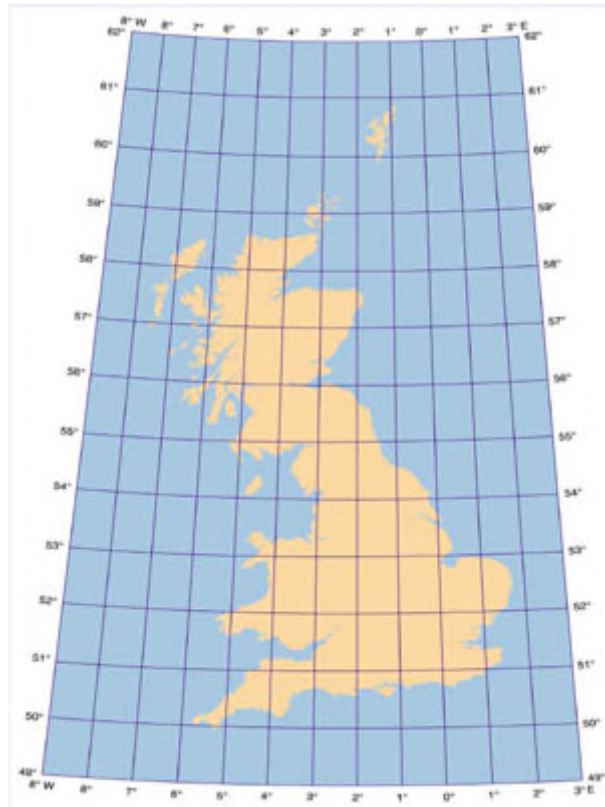


Figure 3-13 The graticule covering Great Britain [38].

The GPS position with Latitude and Longitude in FlightGear property tree is represented in WGS84 coordinate system, while the Cranfield airport map is mapped in OSGB36 National Grid coordinate system. The second block is used to transform the GPS position of own ship from the WGS84 coordinate system to OSGB36 National Grid coordinate system in each simulation time step. The GPS position of own ship will be used to move the map in the figure of MATLAB.

Except the transformation of coordinate system, the rotation aspect also has to be considered in the 'LLAtoOSNG' block. Because the distortion exists when transfer curve surface to flat surface, there is a difference which is known as convergence between the grid on Transverse Mercator projection and the

graticule lines covering on the earth. The relationship between the Grid Bearing (GB), True Bearing (TB) and Convergence (CV) is connected by the following equation 3-2:

$$GB = TB - CV \quad (3-2)$$

Thus, the heading data known as True bearing obtained from the FlightGear needs to be adjusted by convergence when rotating the map drawn on National Grid. This adjustment is completed in the third block called Sum block which is cited from Math Operations library in Simulink.

The fourth block named 'moving map experiment' enables Simulink to display the moving map and fixed airplane symbol, and drive the map to move and rotate in the MATLAB figure according to the position and heading of own ship. In the figures, there are two methods to rotate the map. One method is to fix the axes and modify the position of each graphics according to the rotating centre, the other method is to directly rotate the axes, so the whole graphics in the axes will then rotate. Although the first method shows the rotating effect, it changes the real position of graphics in internal calculation which may cause divergence when real position needs to be accessed. In this research, the second method is adopted to rotate the axes in figures using a concept named as 'camera'. When rotating and moving the camera of the viewing axes, the view of the axes on the screen will rotate and move in the opposite direction. When manipulating the camera up vector, camera view angle, camera position and the location of the camera target in the current axes, the movement of axes will achieved. Thus, the map graphics on the axes will also move and rotate within the axes. Because the input signals of the fourth block are Easting and Northing coordinate and adjusted bearing, the moving map can reflect the position and orientation of the own ship.

3.2.3 Information on the Moving Map

Pilots need to obtain several aspects of information when taxiing on the airdrome. Some of this information, such as the location, the heading and the velocity of the own ship, are displayed on the integrated moving map, and other

guidance information, such as the taxiway designator, compass and guidance lines are also integrated.

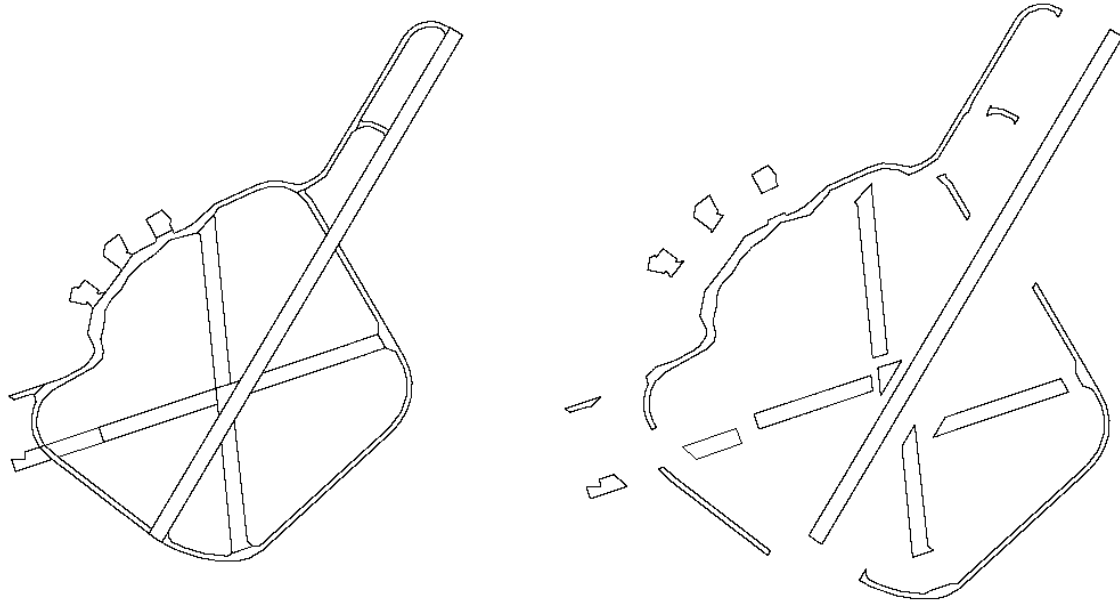


Figure 3-14 Division strategy of the boundaries

The location of own ship is checked by comparing the GPS position of own ship and the boundary of each taxiway, runway and apron. To simplify the calculation, they are treated on the 2-D map which depicts the easting and northing in OSGB36 National Grid coordinates system. As a result, it is necessary to use the previously transformed GPS position which drives the map to move and rotate. According to the boundaries of each taxiway, runway and aprons, the original Ordnance Survey map has to be divided into several separate regions. Figure 3-14 shows the division strategy of the boundaries. There are total seventeen regions which are nine taxiway regions, one runway region, six apron regions and one taxiway cross region used to locate own ship. As all the regions do not intersect with each other, the location of own ship can be determined uniquely.

The boundaries of these regions are described by polygons. An MATLAB function 'inpolygon' is introduced to check whether a point is in the polygon or not. As the polygon is depicted by a series of sequential linked line segments which are called polylines, the coordinates of the end points in the polylines

should be obtained as one of the input parameters in the above MATLAB function. Thus, the edges known as polylines of the polygons should be joined sequentially. An AUTOCAD command 'pedit (PE)' is introduced to join the polylines into polygons. Then, the map coordinates of the polygons can be read by MATLAB after generating the shape files of the polygons. The map coordinates will be organized in matrix which can be used as the input parameters of function 'inpolygon'. The coordinates of the own ship will be checked by all the polygons. If the coordinates are located in one of the polygons, the designator of the polygon is the location of the own ship. If the coordinates are outside of all the polygons, this means the own ship is outside of the taxiway.

There are two approaches to obtain the velocity of own ship. One is to access the velocity in the FlightGear property tree directly, and the other is to calculate the velocity in each simulation time step using the aircraft movement distance between adjacent time steps. The first approach is relatively simple in programming by using the 'httpd' I/O protocol, but will cause relatively long execution time in each simulation time step. The reason for the relatively long execution time may be adopting the 'httpd' I/O protocol to access data from the FlightGear property tree. Other I/O protocols may be more efficient to access data from the FlightGear property tree. In order to improve the efficiency of program execution, the second approach is adopted.

Text information, shape information and colour information are three kinds of information displayed on the head-down display. The taxiway designations, runway designations, Aprons names, velocity and heading are all shown in text, while the airport moving map and aircraft symbols are displayed in shape. The colour information is represented as the property of text and shape. The MATLAB function 'text' is introduced to display the text information on the figures. The property of the text, such as the location, content and colour of the text, has to be controlled according to different functions of the text. The visibility of the text can also be adjusted by the pilots. For example, a trigger button on the head-down display is programmed to display or hide the taxiway

designations, runway designations and Aprons names in order to obtain a detailed display or a succinct display. The trigger button is programmed using the GUI control function in MATLAB.

As it is not convenient to calculate the heading of the own ship through its position, the heading of the own ship is obtained by accessing the FlightGear property tree. It is displayed on the upper centre of the head-down display. The compass is another important feature on the head-down display. The previous method to generate the compass involves directly drawing the compass on the moving map, because the map can be used to indicate the directions. But because there is convergence in the OSGB36 National Grid system, the directions of two points on the map (grid bearing) is not the accurate direction in the real world (true bearing), the equation 3-2 needs to be adopted to eliminate the deviation caused by convergence. Thus, the compass is separated from the moving map and generated in another axes. The rotation of the compass is driven by the heading of the own ship. By rotating the camera of the compass axes in the opposite direction of the heading, the compass will represent the right direction of the own ship.

The function of zooming in and zooming out the moving map needs to be programmed in order to facilitate the pilots to adjust the map to observe the details around the own ship or the whole visual field of map. In order to zoom in and zoom out the map, one of the MATLAB Programmatic GUI called slider is introduced to adjust the view distance property of the camera in the moving map axes. That means all the shape information on the moving map axes can be zoomed in or zoomed out. The slider value can be obtained in MATLAB Callbacks function and it can be modified from minimum to maximum value by moving the slider bar from left to right position.

As shown in Figure 3-15, one of the most important guidance information is the green guidance line on the moving map. The traffic controllers send the guidance line to the own ship. The guidance line leads the own ship taxiing from the apron to the holding point. The traffic controller can update the guidance line

wherever the own ship is. After sending the new guidance line, the previous guidance line will disappear on the head-down display.

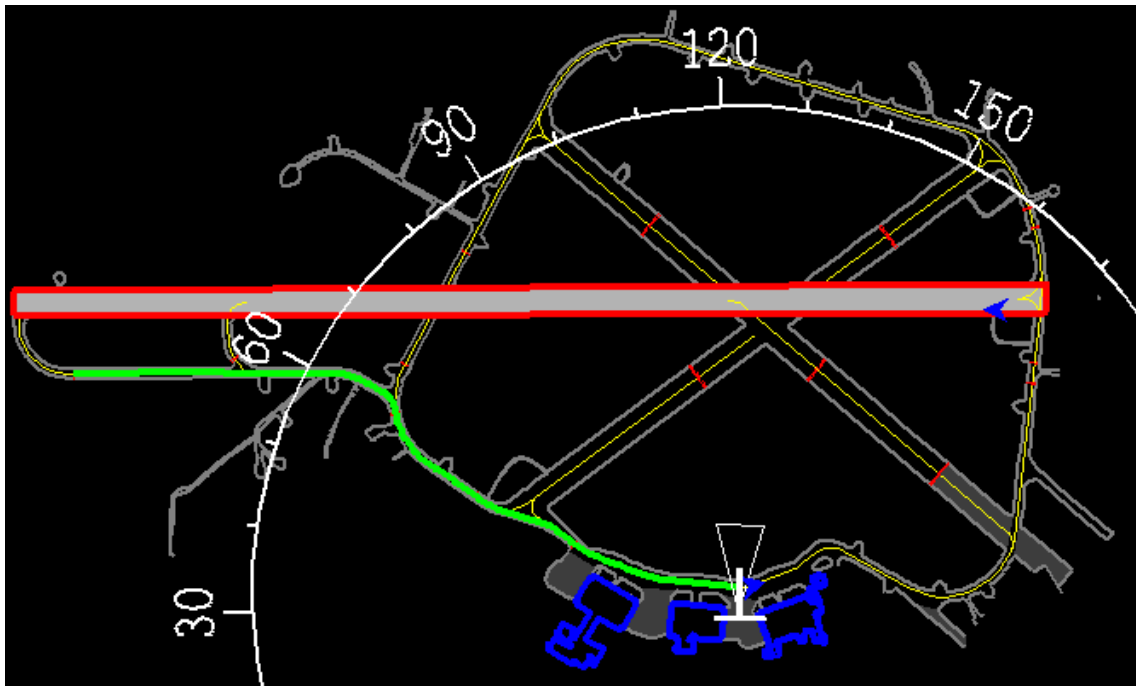


Figure 3-15 The guidance line on the moving map

In order to control the guidance line simultaneously with the moving map, such as rotating and zooming in, the guidance line is drawn in the moving map axes. Obviously, the guidance lines should be coincident with the centre lines of taxiways. Figure 3-16 shows a series of points called guidance points on the taxiway centre lines. These points as the database are used to generate the guidance lines and they are all located on the taxiway centre lines. The method to generate these points is very similar to the previous approach of obtaining the points on the taxiway centre lines when building the airport model. The distance of two adjacent points is about ten metres which is longer than the distance of two adjacent points used to create the curves of taxiway centre lines in FlightGear. The reason for choosing this distance is that it is not necessary to use too many points to generate the guidance lines. Several guidance lines are pre-organised, and the map coordinates of the consequential points in guidance lines are saved in matrix. The program will use these data for generating the guidance lines, if the traffic controllers choose one of these pre-organised

guidance lines. A unique index is used to identify each of the pre-organised guidance lines.

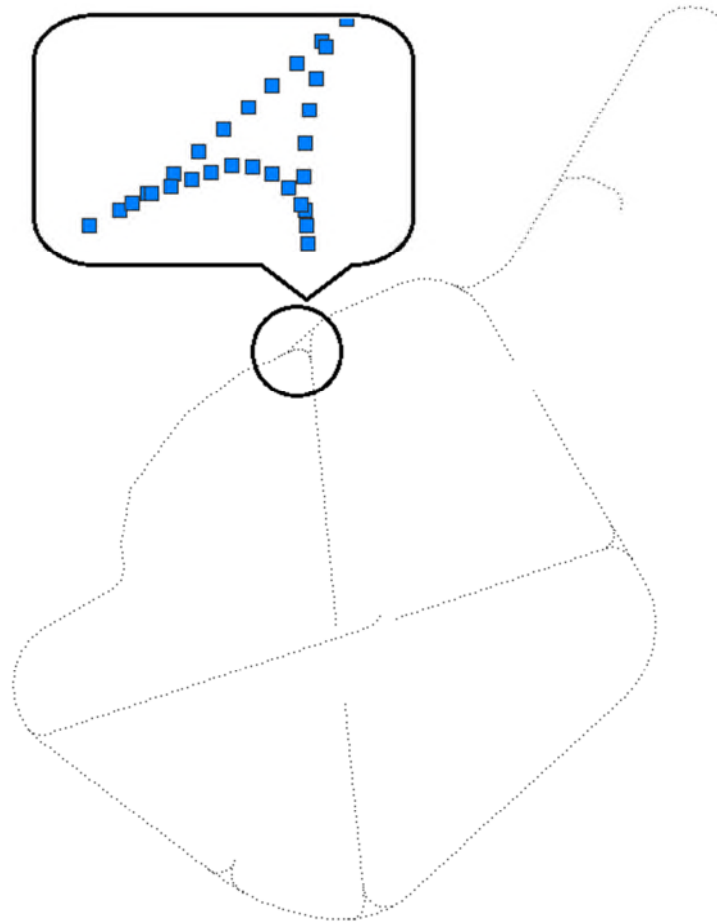


Figure 3-16 The guidance points on the taxiway centre lines

A Simulink block called 'CreatGuidance' is introduced to generate the guidance lines. The block is written in MATLAB Level II S-Function which can receive the index of the guidance line designated by the traffic controllers. There are three input ports and eight output ports on the block. Two input ports are used to receive the map coordinates of the own ship, and the third input port is the switch to control the block receive the index of the guidance line automatically or manually. If the block receives the index of the guidance line manually, the pilots have to trigger a button on the head-down display to receive a new guidance line after getting the command to change the guidance line from the traffic controller by radio. Two output ports service for outputting the map

coordinates of the vertex on the guidance lines; another three output ports are used to output the Cartesian coordinates of the vertex for displaying the guidance lines on head-up display. There are two output ports to transfer the map coordinates of the own ship to the subsequent 'movingmapexperiment' block to drive the moving map. The last output port exports the runway occupation status.

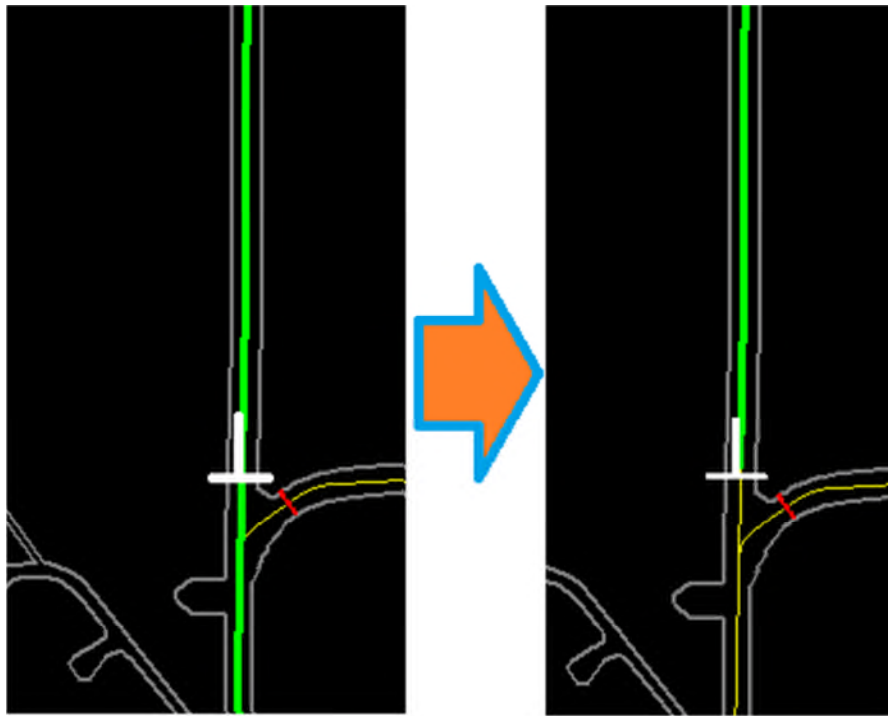


Figure 3-17 Hiding the guidance lines behind the own ship

In the previous research, when the aircraft is taxiing on the guidance lines, the guidance line behind the aircraft is still displayed on the head-down display [39]. This situation may cause direction confusion, because there are two end points on the guidance line, and the pilots may not know which end point is the guidance direction. One solution to solve this problem is hiding the guidance line segments which have been passed by the aircraft. Figure 3-17 shows the solution of displaying the guidance line. The guidance line segments behind the aircraft is disappeared in the picture on the right because the aircraft has passed these guidance line segments. Obviously, just displaying the guidance line segments from the destination to the aircraft has the same effect of erasing the passed line segments. When the aircraft is moving on the guidance line, the

nearest guidance point is found by checking the distance between each guidance point and the own ship position. Then the coordinates of a series of guidance points from the destination to the nearest guidance point are transferred to the subsequent block to display the guidance line on the moving map.

3.3 Head-Up Display System

There is a transparent glass to reflect information on the head-up display to the pilots. Normally, the pilots can watch the taxiways, centre lines of taxiways and holding point markings through the head-up display in good visibility weather conditions. But, in low visibility weather conditions, the visible distance of the taxiways, centre lines of taxiways and holding point markings is very close. An extreme example is when taxiing on the airport at night, pilots missing the way if they are not familiar with the airport.

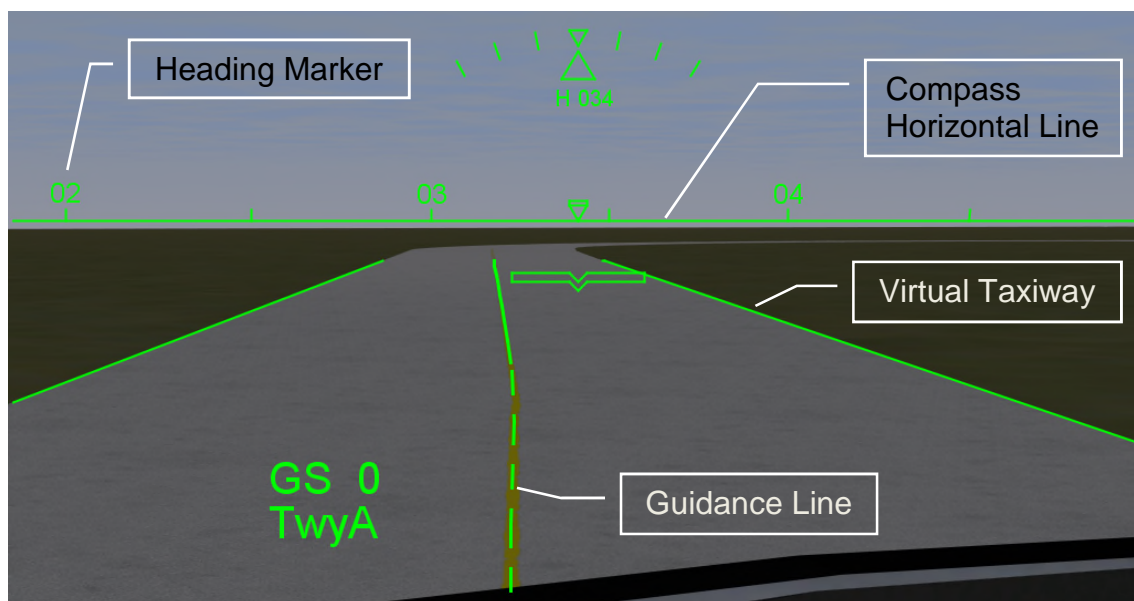


Figure 3-18 The geometry of virtual taxiways and guidance lines on the HUD

The geometry of the guidance lines and the edges of taxiways are mainly used to create a virtual taxiways and guidance lines displayed on the head-up display to guide the pilots. An HUD mini map is introduced to display the moving map on the head-up display. An artificial horizontal line and compass are generated on the head-up display to help pilots to know the directions ahead. Other

information, such as the heading, the rolling, the pitch, the ground speed and the location of the own ship are arranged on the head-up display to provide the basic information of the own ship to the pilots. The guidance caution information is introduced to remind the pilots to taxi on the guidance lines if the own ship deviates the guidance lines.

A method of covering the virtual taxiways and guidance lines on the HUD to the real world taxiways and taxiway centre lines is studied. As shown in Figure 3-18, the geometry of virtual taxiways and guidance lines on the HUD are coincident with the real world if the pilots view the taxiways through the HUD.

Cartesian coordinate system which is shown in Figure 3-19 is introduced as the coordinate system for the HUD guidance information to display the taxiways and the designated guidance lines on the HUD. Compared to other world coordinate systems, Cartesian geocentric coordinate system of the earth benefits internal data processing to represent the taxiway geometry on the curve earth surface on the HUD, and also benefits covering the geometries on the HUD onto the real taxiways.

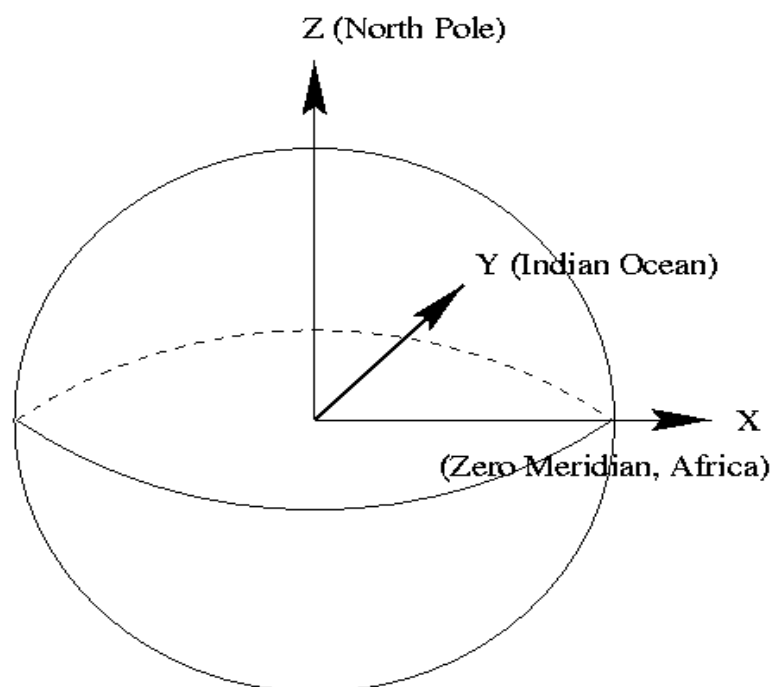


Figure 3-19 Cartesian geocentric coordinate system of earth [40]

There are two kinds of information displaying on the HUD: geometry and text information. The geometries of the taxiways, the guidance lines, the artificial horizontal line and compass, the HUD mini map, the rolling indicator and the symbol of own ship are all geometrical information and their basic geometries are represented by line segments.

3.3.1 The Geometries of the Virtual Taxiways

As FlightGear is the simulation environment to provide the airport model, the core question of displaying the geometries of the virtual taxiways on the HUD is how to coincide the virtual taxiways on the HUD with the taxiways in FlightGear. Computer Graphics is introduced to display the virtual geometries of taxiways on the HUD. Figure 3-20 illustrates the 3D viewing process of transforming the 3D world coordinates to the 2D screen coordinates by five steps. The 3D World coordinates of the edge of the taxiways will be transformed to the 2D screen coordinates to be displayed on the HUD screen through this 3D viewing process.

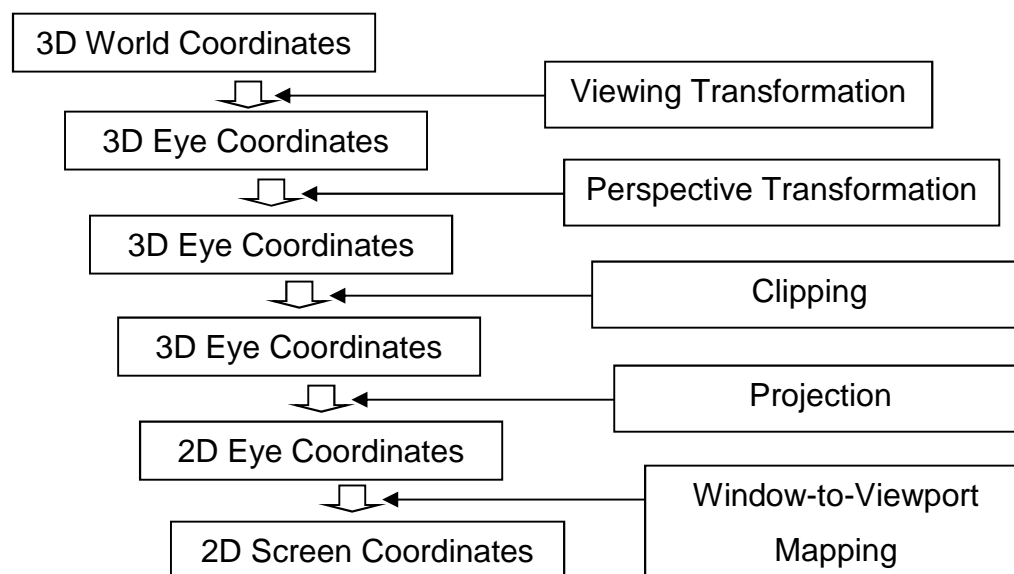


Figure 3-20 The 3D viewing process

The coordinates in Geodetic Coordinate System are represented by the latitude, longitude and ellipsoid height. The geodetic coordinates of the points on the edges of the taxiway are obtained when building the airport model in FlightGear. A software called Grid InQuest published by Ordnance Survey is introduced to transform the geodetic coordinates of all the points on the taxiway edges to the

Cartesian coordinates, known as geocentric coordinates, which are represented by X coordinates, Y coordinates and Z coordinates. These transformed Cartesian coordinates are the 3D World Coordinates.

In the Viewing Transformation step, an eye coordinate frame will be formed and the objects in 3D World will be transformed from world space to eye space. The world space is the Cartesian coordinates system of earth, the origin of the world space is the centre of earth. However, the eye space is established by the eye coordinate frame. There are three orthogonal basis vectors emitted from the origin: the normal vector (**n**) of the viewing plane, and two vectors (**u** and **v**) that span the viewing plane. The origin of the eye coordinate frame is the eye position. The relationship between the eye coordinate frame and the world space is illustrated in Figure 3-21. The vector **v**, **u**, **n** are the three orthogonal basic vectors, the 3D world coordinates of the eye is represented by (ex, ey, ez). The point P is the point being observed in the world space. Vector n is pointing away from the point P.

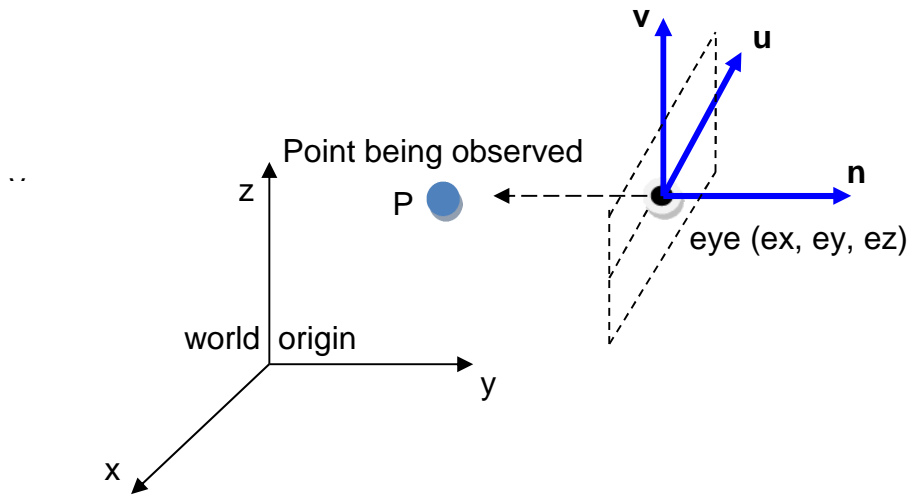


Figure 3-21 The eye coordinate frame and the world space

The coordinates of P in the eye coordinate frame is represented by P_e . The relationship between P and P_e is depicted in equation 3-3 [41].

$$P_e = M_{w2e} P \quad (3-3)$$

The coordinates of P and P_e is represented by homogeneous coordinates. The transformation matrix for viewing transformation M_{w2e} is calculated according to equation 3-4 [41].

$$\mathbf{M}_{w2e} = \begin{bmatrix} ux & uy & uz & 0 \\ vx & vy & vz & 0 \\ nx & ny & nz & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & -ex \\ 0 & 1 & 0 & -ey \\ 0 & 0 & 1 & -ez \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3-4)$$

The coordinate representations of vector **u** ([ux uy uz]), **v** ([vx vy vz]), **n** ([nx ny nz]) and the 3D world coordinates of eye (ex, ey, ez) need to be calculated. These coordinates are all represented in the Cartesian coordinate system of earth.

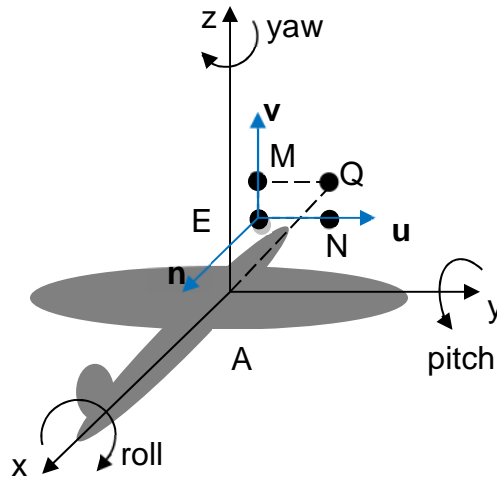


Figure 3-22 The airplane 3D mode in the airplane coordinate system

According to the documents of airplane model in FlightGear, the position of eye point is located in the coordinate system of the airplane 3D model which is shown in Figure 3-22. The origin point A is defined as the centre of gravity of the airplane. The x-axis runs lengthwise, towards the back. The y-axis runs sideways, towards the right. The z-axis runs upwards. The point E is the position of the eye point. The airplane 3D mode coordinates of the eye point E is (T_x, T_y, T_z). The point Q is on the x-axis in the airplane coordinate system. The point Q will be used to derive the rotation transformation matrix. As shown in the

Figure 3-22, the line EM coincides with the basis vector \mathbf{v} and the line EN coincides with the basis vector \mathbf{u} .

The geodetic coordinates of airplane GPS position can be obtained from FlightGear by accessing the FlightGear property tree. As Simulink cannot call the software Grid InQuest, another approach to transform the geodetic coordinates to Cartesian geocentric coordinates should be introduced to build the transformation block in Simulink. The geocentric coordinates (X, Y, Z) are related to the geodetic coordinates (λ, φ, h) by the following formulae [42]:

$$X = (h + n) \cos \varphi \cos \lambda \quad (3-5)$$

$$Y = (h + n) \cos \varphi \sin \lambda \quad (3-6)$$

$$Z = (h + n - e^2 n) \sin \varphi \quad (3-7)$$

where

$$n = \frac{a}{\sqrt{1 - e^2 \sin^2 \varphi}} \quad (3-8)$$

The semi-major axis of the ellipse, a , is identified as the equatorial radius of the reference ellipsoid (WGS84) and the e is the eccentricity of reference ellipsoid (WGS84). The X, Y, Z are the Cartesian geocentric coordinates. The λ, φ, h are the geodetic longitude, geodetic latitude, geodetic height (ellipsoid height) of the geodetic coordinates. According to the above formulae, the Cartesian geocentric coordinates of centre of gravity (point A) can be calculated through the geodetic coordinates.

The centre point of gravity is defined as the GPS position of the airplane in FlightGear. Thus, a method to find the eye point coordinates should be defined according to the centre point of gravity. As mentioned before, the eye point coordinates in airplane model coordinate system is defined in the documents of airplane model in FlightGear. The following figures from 3-23 to 3-27 illustrate the transformation from the airplane model coordinates to the Cartesian

geocentric coordinates. There are four main steps to transform the eye point coordinates. The first step is translating the centre of gravity (point A) to the eye point. The second to fourth steps are rotating the eye point according to the yaw, pitch and roll of the airplane. Each above step will generate a transformation matrix.

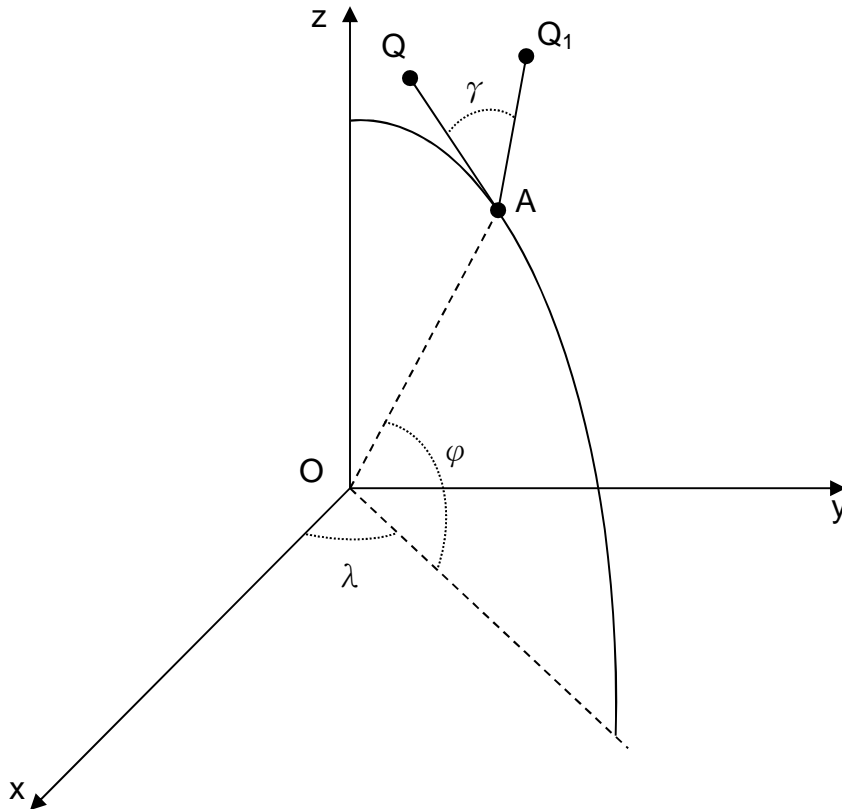


Figure 3-23 The rotation transformation according to yaw

The Figure 3-23 illustrates the rotation transformation according to yaw. The γ represents the degree of yaw. Point Q1 is the updated position of point Q after rotate γ degrees around straight line OA.

There are several steps to generate the translational transformation matrix. First, translate the centre of gravity (point A) to the origin (point O). The transformation matrix T_{tA} is shown in equation 3-9. The X_A , Y_A , Z_A are the Cartesian geocentric coordinates of centre of gravity (point A).

$$\mathbf{T}_{tA} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -X_A & -Y_A & -Z_A & 1 \end{bmatrix} \quad (3-9)$$

Second, rotate the z-axis through an angle $-\lambda$ to locate the line OA on the x-z plane. The transformation matrix \mathbf{T}_{Rz} is shown in equation 3-10.

$$\mathbf{T}_{Rz} = \begin{bmatrix} \cos(-\lambda) & \sin(-\lambda) & 0 & 0 \\ -\sin(-\lambda) & \cos(-\lambda) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3-10)$$

Third, rotate the y-axis through an angle $(\pi/2 - \varphi)$ to align the straight line OA with z-axis. The transformation matrix \mathbf{T}_{Ry} is shown in equation 3-11.

$$\mathbf{T}_{Ry} = \begin{bmatrix} \cos[-(\frac{\pi}{2} - \varphi)] & 0 & -\sin[-(\frac{\pi}{2} - \varphi)] & 0 \\ 0 & 1 & 0 & 0 \\ \sin[-(\frac{\pi}{2} - \varphi)] & 0 & \cos[-(\frac{\pi}{2} - \varphi)] & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3-11)$$

Fourth, when the straight line OA is aligned with the z-axis, applying the original translation by translate point A to point E use the transformation matrix \mathbf{T}_{tE} as in equation 3-12.

$$\mathbf{T}_{tE} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ T_x & T_y & T_z & 1 \end{bmatrix} \quad (3-12)$$

Fifth, apply the inverses of the transformations in reverse order. The translational transformation matrix T_{tAE} for translating the centre of gravity (point A) to the eye point (point E) is shown in equation 3-13.

$$T_{tAE} = T_{tA} T_{Rz} T_{Ry} T_{tE} T_{Ry}^{-1} T_{Rz}^{-1} T_{tA}^{-1} \quad (3-13)$$

After translating point A to the eye point (point E), the Cartesian geocentric coordinates of point E can be calculated according to equation 3-14.

$$E = [X_A \quad Y_A \quad Z_A \quad 1] T_{tAE} \quad (3-14)$$

There are also several steps to generate the rotation transformation matrix according to the degree of yaw γ . The transformation matrix of the first three steps is the same as equation 3-9, 3-10, 3-11. When the straight line OA is aligned with the z-axis, applying the original rotation by rotating the z-axis through an angle $-\gamma$. The transformation matrix T_{Rz2} is shown in equation 3-15.

$$T_{Rz2} = \begin{bmatrix} \cos(-\gamma) & \sin(-\gamma) & 0 & 0 \\ -\sin(-\gamma) & \cos(-\gamma) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3-15)$$

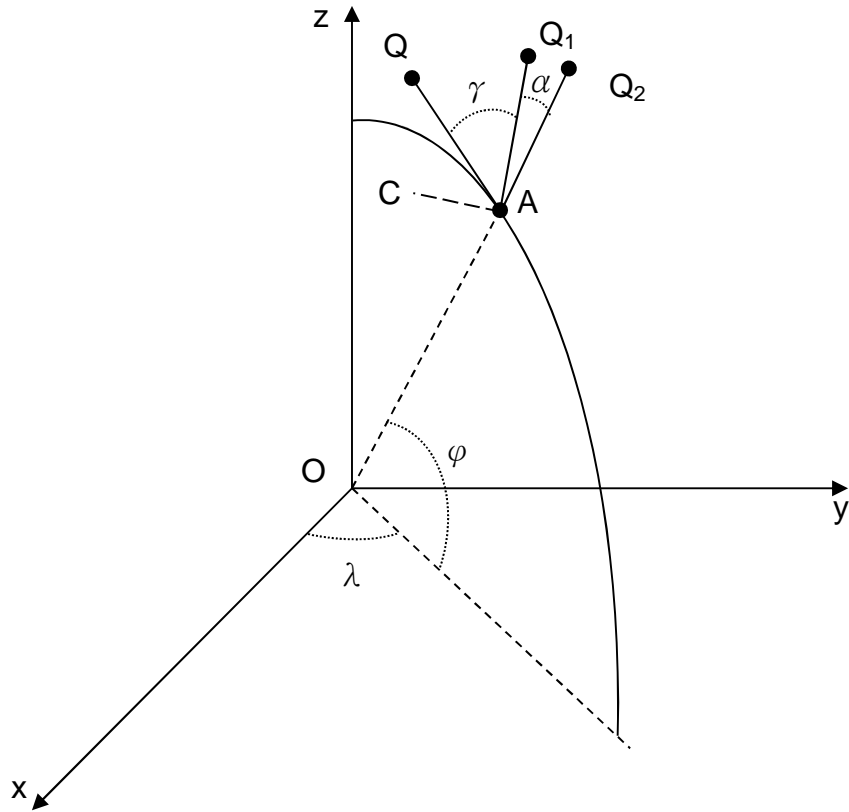


Figure 3-24 The rotation transformation according to pitch

Thus, the rotation transformation matrix T_{RAO} for rotating the eye point according to the yaw is shown in equation 3-16.

$$T_{RAO} = T_{tA} T_{Rz} T_{Ry} T_{Rz2} T_{Ry}^{-1} T_{Rz}^{-1} T_{tA}^{-1} \quad (3-16)$$

After rotating the straight line OA through a degree of yaw (γ), the Cartesian geocentric coordinates of the eye point E_1 can be calculated according to equation 3-17.

$$E_1 = E T_{RAO} \quad (3-17)$$

Figure 3-24 illustrates the rotation transformation according to pitch. The point Q_2 is the updated point of point Q_1 after rotating the straight line AC through a degree of pitch (α). The straight line AC is the rotation axis of pitch in the

airplane coordinate system. There are several steps to generate the rotation transformation matrix according to the degree of pitch α . The transformation matrix of the initial three steps is the same as equation 3-9, 3-10, 3-11. When the straight line OA is aligned with the z-axis, apply the original rotation by rotating the z-axis through an angle γ as shown in Figure 3-25. The transformation matrix T_{Rz3} is shown in equation 3-18.

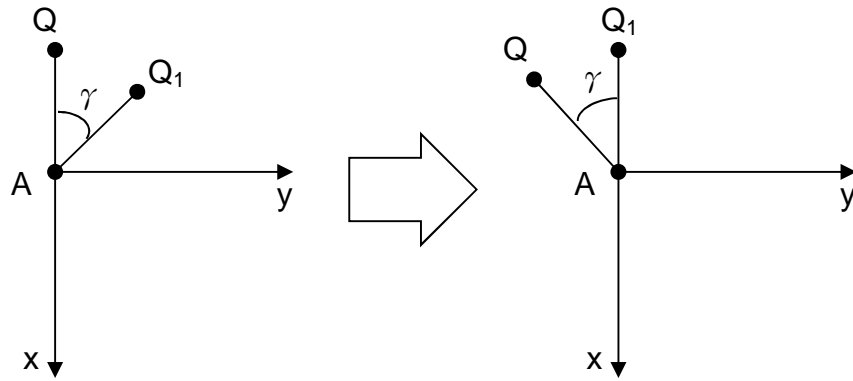


Figure 3-25 The rotation around z-axis through an angle γ

$$\mathbf{T}_{Rz3} = \begin{bmatrix} \cos(\gamma) & \sin(\gamma) & 0 & 0 \\ -\sin(\gamma) & \cos(\gamma) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(3-18)

Then, rotate the x-axis through -90 degrees, the rotation axis of pitch (line AC) will align with z-axis. The transformation matrix T_{Rx} is shown in equation 3-19.

$$\mathbf{T}_{Rx} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(-\frac{\pi}{2}) & \sin(-\frac{\pi}{2}) & 0 \\ 0 & -\sin(-\frac{\pi}{2}) & \cos(-\frac{\pi}{2}) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(3-19)

The next step is applying the original rotation about the z-axis through an degree of pitch ($-\alpha$). The transformation matrix T_{Rz4} is shown in equation 3-20.

$$\mathbf{T}_{Rz4} = \begin{bmatrix} \cos(-\alpha) & \sin(-\alpha) & 0 & 0 \\ -\sin(-\alpha) & \cos(-\alpha) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(3-20)

Thus, the rotation transformation matrix \mathbf{T}_{RAC} for rotating the eye point according to the pitch is shown in equation 3-21.

$$\mathbf{T}_{RAC} = \mathbf{T}_{tA} \mathbf{T}_{Rz} \mathbf{T}_{Ry} \mathbf{T}_{Rz3} \mathbf{T}_{Rx} \mathbf{T}_{Rz4} \mathbf{T}_{Rx}^{-1} \mathbf{T}_{Rz3}^{-1} \mathbf{T}_{Ry}^{-1} \mathbf{T}_{Rz}^{-1} \mathbf{T}_{tA}^{-1}$$

(3-21)

After rotating the straight line AC through a degree of pitch (α), the Cartesian geocentric coordinates of the eye point E_2 can be calculated according to equation 3-22.

$$\mathbf{E}_2 = \mathbf{E}_1 \mathbf{T}_{RAC}$$

(3-22)

Obviously, the line AQ_2 is the rotation axis of roll. In order to derive the rotation transformation matrix of roll, the following steps need to be performed to align the line AQ_2 with z-axis. The transformation matrix of the initial five steps is the same as equation 3-9, 3-10, 3-11, 3-18, 3-19. When the straight line AC is aligned with the z-axis, rotating the z-axis through an angle α (pitch) as shown in Figure 3-26. The transformation matrix \mathbf{T}_{Rz5} is shown in equation 3-23.

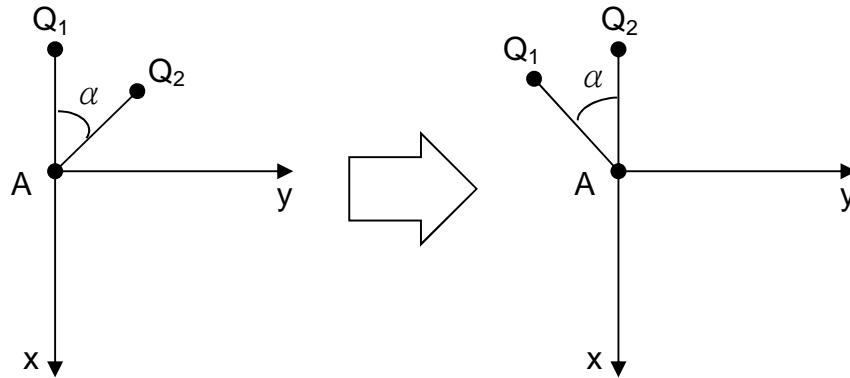


Figure 3-26 The rotation around z-axis through an angle α

$$\mathbf{T}_{Rz5} = \begin{bmatrix} \cos(\alpha) & \sin(\alpha) & 0 & 0 \\ -\sin(\alpha) & \cos(\alpha) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(3-23)

Then, rotate y-axis through 90 degrees to align the line AQ_2 with z-axis. The rotation transformation matrix \mathbf{T}_{Ry2} is shown in equation 3-24.

$$\mathbf{T}_{Ry2} = \begin{bmatrix} \cos \frac{\pi}{2} & 0 & -\sin \frac{\pi}{2} & 0 \\ 0 & 1 & 0 & 0 \\ \sin \frac{\pi}{2} & 0 & \cos \frac{\pi}{2} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(3-24)

Figure 3-27 illustrates the above rotation result, the line AQ_2 is coincident with the z-axis. The eye point E_2 will rotate around z-axis through an angle β (roll). The rotation transformation matrix \mathbf{T}_{Rz6} is shown in equation 3-25.

$$\mathbf{T}_{Rz6} = \begin{bmatrix} \cos(\beta) & \sin(\beta) & 0 & 0 \\ -\sin(\beta) & \cos(\beta) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(3-25)

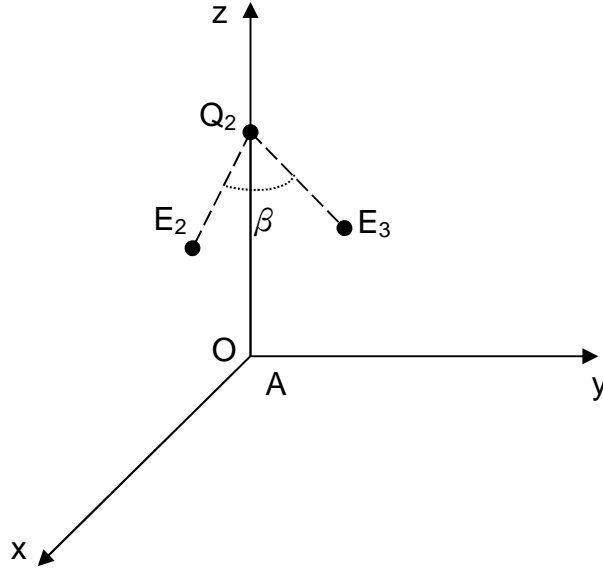


Figure 3-27 The rotation around z-axis through an angle β (roll)

Thus, the rotation transformation matrix T_{RAQ} for rotating the eye point according to the roll is shown in equation 3-26.

$$T_{RAQ} = T_{tA} T_{Rz} T_{Ry} T_{Rz3} T_{Rx} T_{Rz5} T_{Ry2} T_{Rz6} T_{Ry2}^{-1} T_{Rz5}^{-1} T_{Rx}^{-1} T_{Rz3}^{-1} T_{Ry}^{-1} T_{Rz}^{-1} T_{tA}^{-1} \quad (3-26)$$

The Cartesian geocentric coordinates of the eye point E_3 can be calculated according to equation 3-27. The point E_3 is the final eye position after translation, yaw, pitch and roll.

$$E_3 = E_2 \square T_{RAQ} \quad (3-27)$$

Till now, the Cartesian geocentric coordinates of the eye point, known as the 3D world coordinates of eye (ex , ey , ez) in the equation 3-4, are obtained through the above transformation.

In order to solve the basis vectors (\mathbf{u} , \mathbf{v} and \mathbf{n}) of the eye coordinate frame, the Cartesian geocentric coordinates of the point N and M in Figure 3-22 need to be calculated. Then the basis vectors can be solved by equations 3-28, 3-29 and 3-30.

$$\vec{u} = \frac{\overrightarrow{EN}}{|\overrightarrow{EN}|}$$

(3-28)

$$\vec{v} = \frac{\overrightarrow{EM}}{|\overrightarrow{EM}|}$$

(3-29)

$$\vec{n} = \vec{u} \times \vec{v}$$

(3-30)

The coordinates of point N in the airplane coordinate system is (T_x , 0, T_z). Similar to the transformation approach to calculate the coordinates of the eye point, the Cartesian geocentric coordinates of the point N can be solved by equations 3-31 to 3-36.

$$\mathbf{T}_{tN} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ T_x & 0 & T_z & 1 \end{bmatrix}$$

(3-31)

$$\mathbf{T}_{tAN} = \mathbf{T}_{tA} \mathbf{T}_{Rz} \mathbf{T}_{Ry} \mathbf{T}_{tN} \mathbf{T}_{Ry}^{-1} \mathbf{T}_{Rz}^{-1} \mathbf{T}_{tA}^{-1}$$

(3-32)

$$\mathbf{N} = [X_A \quad Y_A \quad Z_A \quad 1] \mathbf{T}_{tAN}$$

(3-33)

$$\mathbf{N}_1 = \mathbf{N} \square \mathbf{T}_{RAO}$$

(3-34)

$$\mathbf{N}_2 = \mathbf{N}_1 \square \mathbf{T}_{RAC}$$

(3-35)

$$\mathbf{N}_3 = \mathbf{N}_2 \square \mathbf{T}_{RAQ}$$

(3-36)

The point N_3 is the final position of point N after translation, yaw, pitch and roll.

The coordinates of point M in the airplane coordinate system is $(T_x, T_y, 0)$. Similar to the transformation approach to calculate the coordinates of the eye point, the Cartesian geocentric coordinates of the point M can be solved by equations 3-37 to 3-42.

$$\mathbf{T}_{tM} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ T_x & T_y & 0 & 1 \end{bmatrix}$$

(3-37)

$$\mathbf{T}_{tAM} = \mathbf{T}_{tA} \mathbf{T}_{Rz} \mathbf{T}_{Ry} \mathbf{T}_{tM} \mathbf{T}_{Ry}^{-1} \mathbf{T}_{Rz}^{-1} \mathbf{T}_{tA}^{-1}$$

(3-38)

$$\mathbf{M} = [X_A \quad Y_A \quad Z_A \quad 1] \mathbf{T}_{tAM}$$

(3-39)

$$\mathbf{M}_1 = \mathbf{M} \mathbf{T}_{RAO}$$

(3-40)

$$\mathbf{M}_2 = \mathbf{M}_1 \mathbf{T}_{RAC}$$

(3-41)

$$\mathbf{M}_3 = \mathbf{M}_2 \mathbf{T}_{RAQ}$$

(3-42)

The point M_3 is the final position of point M after translation, yaw, pitch and roll. The basis vectors in eye coordinate frame can be solved by the equation 3-28, 3-29 and 3-30. Finally, the transformation matrix for viewing transformation M_{W2e} can be solved by submitting the basis vector and the coordinates of the eye point into equation 3-4. As the transformation matrix is very complicated, it may consume considerable time in each Simulink time step to calculate the above equations. As the Matlab language is an advanced computer language,

the efficiency of Matlab calculation is also a challenge to the computational efficiency.

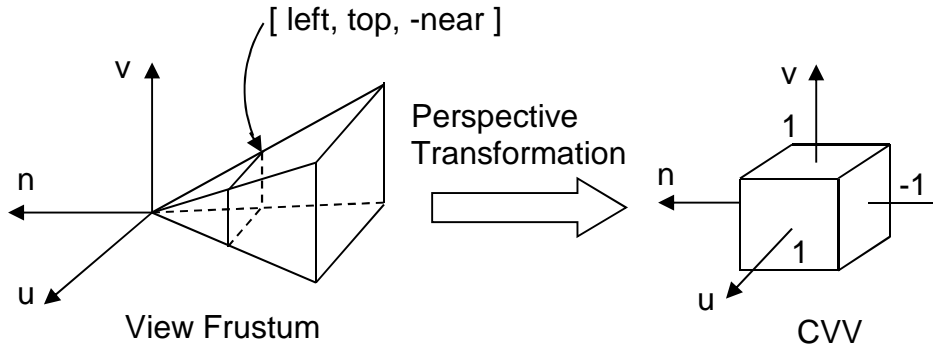


Figure 3-28 The perspective transformation from View Frustum to CVV

After viewing transformation, the vertex in the 3D World coordinate system will be transformed to the eye space which is formed by the eye coordinate frame. The polygons may be clipped by the view frustum, but it is not convenient to clip the polygons in the anomalous view volume. As shown in Figure 3-28, Hill and Kelley provided a Canonical View Volume (CVV) for clipping [41]. the CVV is a cube, the range of x, y and z are all [-1,1]. The clipping is implemented in the CVV. The perspective transformation matrix for transforming the View Frustum to CVV is defined in equation 3-43 [41], where the 'left' and 'right' is the range of u-axis coordinates value on the near plane of view frustum , the 'top' and 'bottom' is the range of v-axis coordinates value on the near plane of view frustum, the 'near' is the distance from the eye position to the near plane of view frustum, and the 'far' is the distance from the eye position to the far plane of view frustum.

$$\mathbf{M}_{\text{per}} = \begin{bmatrix} \frac{2 \cdot \text{near}}{\text{right} - \text{left}} & 0 & \frac{\text{right} + \text{left}}{\text{right} - \text{left}} & 0 \\ 0 & \frac{2 \cdot \text{near}}{\text{top} - \text{bottom}} & \frac{\text{top} + \text{bottom}}{\text{top} - \text{bottom}} & 0 \\ 0 & 0 & \frac{-(\text{far} + \text{near})}{\text{far} - \text{near}} & \frac{-2 \cdot \text{far} \cdot \text{near}}{\text{far} - \text{near}} \\ 0 & 0 & -1 & 0 \end{bmatrix}$$

(3-43)

It is not convenient to obtain the parameter 'left', 'right', 'top' and 'bottom' directly. The items 'fov' and 'aspect' are introduced to calculate the above four parameters. As illustrated in Figure 3-29, the 'fov' is the open angle of the view frustum on **v-n** plane. The 'aspect' is the aspect ratio of the projection plane. The relationship among these parameters is depicted in equations 3-44 to 3-47.

$$top = near \tan\left(\frac{fov}{2}\right)$$

(3-44)

$$bottom = -top$$

(3-45)

$$right = top \times aspect$$

(3-46)

$$left = -right$$

(3-47)

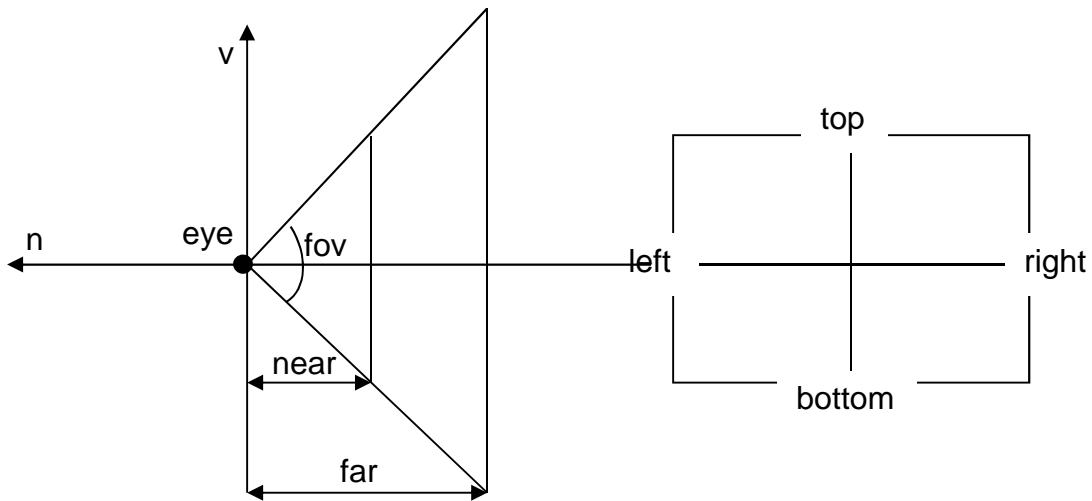


Figure 3-29 The parameters about the view frustum

Finally, the coordinates of point P_{CVV} in the CVV space can be obtained by multiplying the transformation matrix M_{per} with the coordinates of point P_e in the eye space. Their relationship is depicted in equation 3-48.

$$\mathbf{P}_{CVV} = \mathbf{M}_{per} \mathbf{P}_e$$

(3-48)

Not all the points in the CVV space are visible, only the points in the CVV cube are visible by the eye. The points outside the CVV cube will be clipped in the clipping step. The Liang-Barsky Algorithm is introduced to clip the points and lines outside the CVV [41].

As the coordinates of points are represented by homogeneous coordinates $[wu, wv, wn, w]$, the transformation results of the points are also represented by homogeneous coordinates. In order to obtain the normal coordinates (u, v, n) , all the components of homogeneous coordinates need to be divided by the fourth component (w) , then, the fourth component needs to be abandoned.

In the projection step, the first and second components (u_{CVV}, v_{CVV}) of the normal coordinates in the CVV space are used as the coordinates on the projection plane. In the window-to-viewport mapping process, the projection plane (the near plane in the view frustum) is known as the window, the rectangular region on device (computer screen) is called the viewport. The coordinates (u_{CVV}, v_{CVV}) on the window will be transformed to the coordinates (X_s, Y_s) on the device by the equation 3-49, where the V_{width} is the width of the viewport, the V_{length} is the height of the viewport, the V_h is the distance between the top edge of the viewport and the top edge of the device, the V_l is the distance between the left edge of the viewport and the left edge of the device. All these parameters are shown in Figure 3-30.

$$\begin{cases} X_s = \frac{V_{width}(1+u_{CVV})}{2} + V_l \\ Y_s = \frac{V_{length}(1-v_{CVV})}{2} + V_h \end{cases}$$

(3-49)

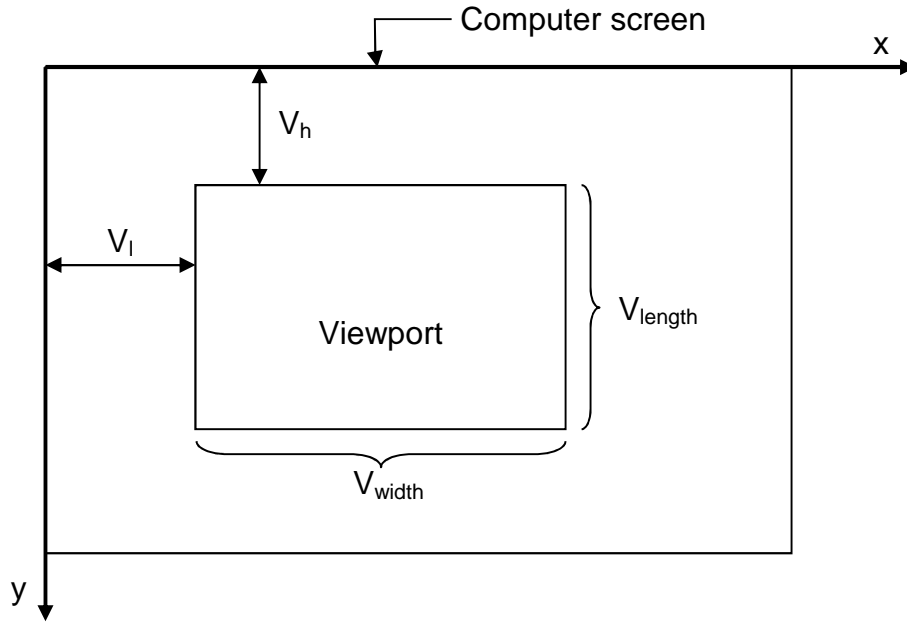


Figure 3-30 The viewport on the computer screen

Apparently, the viewport is the place to display the HUD geometries. In order to coincide the geometries of virtual taxiways on the HUD with the taxiways in the FlightGear, the parameter 'fov' of the HUD needs to be calculated by the equation 3-50. The angle value (FOV) of the captain's field of view can be accessed through the FlightGear property tree, but the captain's field of view is not the same with the viewport of HUD. Their relationship is illustrated in Figure 3-31. The captain's field of view is the outside square whose length and width are both equal to the width (S_{width}) of the computer screen shown in grey. The green viewport known as the HUD is located in the middle of the computer screen. The relationship between the FOV and 'fov' is shown in equation 3-50.

$$\frac{V_{length}}{S_{width}} = \frac{\tan(\frac{fov}{2})}{\tan(\frac{FOV}{2})}$$

(3-50)

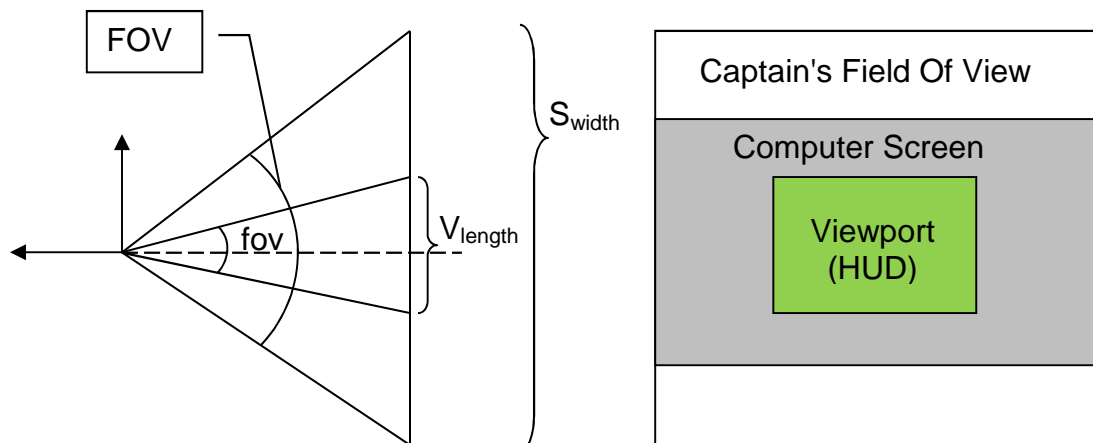


Figure 3-31 The viewport and the captain's field of view

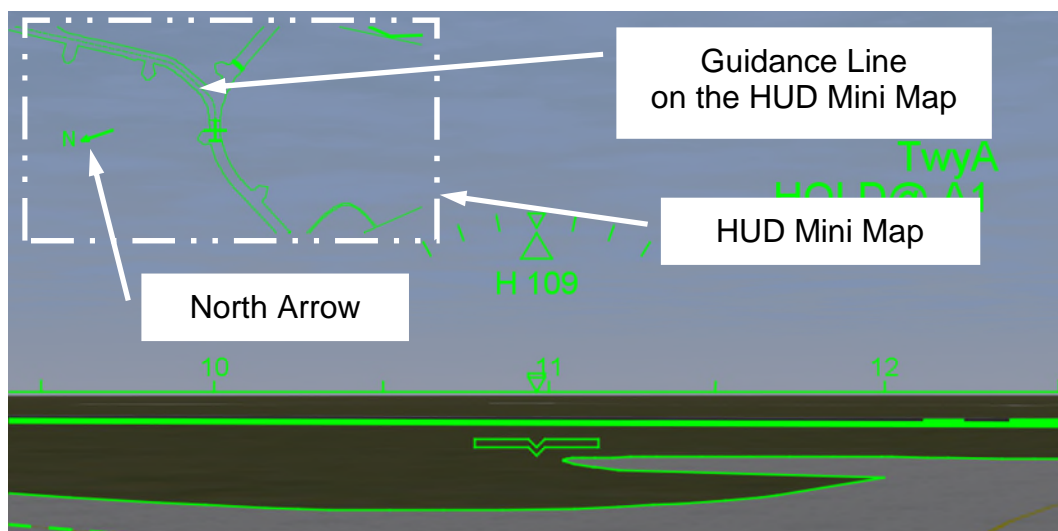


Figure 3-32 The geometries of HUD mini map

3.3.2 The Geometries of HUD Mini Map

As shown in Figure 3-32, the HUD mini map is a moving map displayed in the top left corner of the HUD. It benefits the pilots to aware the position of the own ship. The fixed thick cross in the centre of the mini map is the position of the own ship. The dash line on the mini map represents the guidance line.

The procedure to generate the mini map is the same as the 3D viewing process in Figure 3-20, but the transformation matrix in viewing transformation and the parameters in window-to-viewport mapping are different with those when generating the virtual taxiways on the HUD.

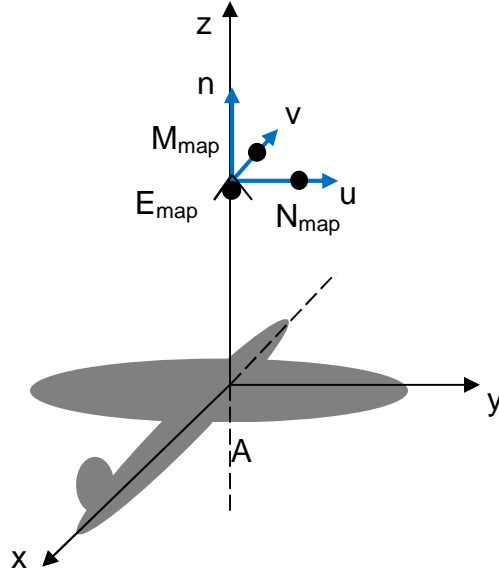


Figure 3-33 The eye coordinates frame of the mini map

The eye coordinates frame of the mini map is shown in Figure 3-33. The eye point E_{map} is located above the centre of gravity of the airplane and the viewing direction is from the eye point E_{map} to the centre of gravity. Considering about the range of the airport field, the height T_{ze} of the E_{map} is set to 1000 meters. The coordinates of the E_{map} in the airplane coordinate system are defined as $(0, 0, T_{ze})$. When changing the 'fov' of the eye coordinate frame the visible area of the airport will be changed correspondingly. Then, a zoom-in and zoom-out effect of the mini map will be displayed. The point M_{map} is located on the vector \mathbf{v} and the point N_{map} is located on the vector \mathbf{u} . The coordinates of point M_{map} and N_{map} in the airplane coordinate system are $(-1, 0, T_{ze})$ and $(0, 1, T_{ze})$. The three points E_{map} , M_{map} and N_{map} are used to generate the viewing transformation matrix according to equation 3-4. The coordinates of point E_{map} is calculated according to equation 3-51 to 3-53. The transformation matrix T_{tEmap} is used for transforming the point A to the point E_{map} in the airplane coordinate system.

$$\mathbf{E}_{map} = [X_A \quad Y_A \quad Z_A \quad 1] \mathbf{T}_{tAEmap} \quad (3-51)$$

$$\mathbf{T}_{tA\text{Emap}} = \mathbf{T}_{tA} \mathbf{T}_{Rz} \mathbf{T}_{Ry} \mathbf{T}_{t\text{Emap}} \mathbf{T}_{Ry}^{-1} \mathbf{T}_{Rz}^{-1} \mathbf{T}_{tA}^{-1} \quad (3-52)$$

$$\mathbf{T}_{t\text{Emap}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & T_{ze} & 1 \end{bmatrix} \quad (3-53)$$

The coordinates of point N_{map} is calculated according to equations 3-54 to 3-56. The transformation matrix $\mathbf{T}_{tN\text{map}}$ is used for transforming the point A to the point N_{map} in the airplane coordinate system.

$$\mathbf{T}_{tN\text{map}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & T_{ze} & 1 \end{bmatrix} \quad (3-54)$$

$$\mathbf{T}_{tAN\text{map}} = \mathbf{T}_{tA} \mathbf{T}_{Rz} \mathbf{T}_{Ry} \mathbf{T}_{tN\text{map}} \mathbf{T}_{Ry}^{-1} \mathbf{T}_{Rz}^{-1} \mathbf{T}_{tA}^{-1} \quad (3-55)$$

$$\mathbf{N}_{\text{map}} = \begin{bmatrix} X_A & Y_A & Z_A & 1 \end{bmatrix} \mathbf{T}_{tAN\text{map}} \mathbf{T}_{RAO} \quad (3-56)$$

The coordinates of point M_{map} is calculated according to equations 3-57 to 3-59. The transformation matrix $\mathbf{T}_{tM\text{map}}$ is used for transforming the point A to the point M_{map} in the airplane coordinate system.

$$\mathbf{T}_{tM\text{map}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -1 & 0 & T_{ze} & 1 \end{bmatrix} \quad (3-57)$$

$$\mathbf{T}_{tAMmap} = \mathbf{T}_{tA} \mathbf{T}_{Rz} \mathbf{T}_{Ry} \mathbf{T}_{tMmap} \mathbf{T}_{Ry}^{-1} \mathbf{T}_{Rz}^{-1} \mathbf{T}_{tA}^{-1}$$

(3-58)

$$\mathbf{M}_{map} = \begin{bmatrix} X_A & Y_A & Z_A & 1 \end{bmatrix} \mathbf{T}_{tAMmap} \mathbf{T}_{RAO}$$

(3-59)

Then the basis vectors in the eye coordinates frame of the mini map can be solved by equations 3-60 to 3-62.

$$\vec{u}_{map} = \frac{\overrightarrow{E_{map} N_{map}}}{\left| \overrightarrow{E_{map} N_{map}} \right|}$$

(3-60)

$$\vec{v}_{map} = \frac{\overrightarrow{E_{map} M_{map}}}{\left| \overrightarrow{E_{map} M_{map}} \right|}$$

(3-61)

$$\vec{n}_{map} = \vec{u}_{map} \times \vec{v}_{map}$$

(3-62)

Finally, the viewing transformation matrix of HUD mini map can be generated by submitting the coordinates of the basis vectors and the eye point coordinates of the HUD mini map into equation 3-4.

Because the HUD mini map is located in the top left corner of the HUD, the viewport size (V_{length} and V_{width}) of the mini map is smaller than the viewport size of the HUD. Another parameter 'far' in the perspective transformation matrix in equation 3-43 should be set to larger than T_{ze} , because the view frustum of the mini map should clip the airport. That means the view frustum should be large enough to make the airport visible.

3.3.3 The Geometries of Compass Horizontal Line

The compass horizontal line, shown in Figure 3-18, is used to indicate the artificial horizontal line and indicate the attitude and the direction ahead. It is combined with an artificial horizontal line and several heading markers. The

model of compass horizontal line is similar to the attitude indicator. The artificial horizontal line on the attitude indicator will be projected on the HUD plane. The model of compass horizontal line is illustrated in Figure 3-34.

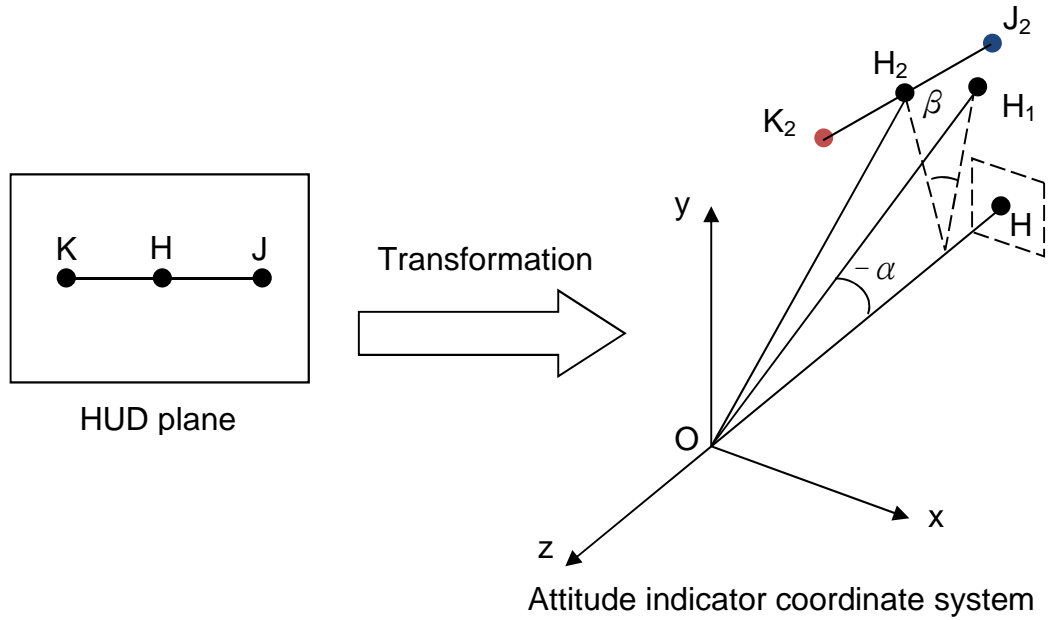


Figure 3-34 The model of compass horizontal line

The position and slope of the compass horizontal line are controlled by pitch and roll. In the model of compass horizontal line, the line KJ is the initial horizontal line when the degrees of the pitch and roll are zero. The point H is the centre point of line KJ and it is also the centre point of the HUD plane. The attitude indicator coordinate system is established to implement the transformation of pitch and roll. The straight line OH is coincident with the z-axis and perpendicular to the HUD plane. The x-axis is parallel to the HUD plane and pointing right of the HUD plane. The distance of the origin point O to the HUD plane is defined by equation 3-63, where the Vlength is the height of the HUD viewport, the 'fov' is the field of view of the eye frustum which used to generate the virtual taxiways. The parameter 'fov' here is the same parameter in equation 3-50. Thus, the initial coordinates of point H, K and J are $(0, 0, -|OH|)$, $(-|KH|, 0, -|OH|)$ and $(|KH|, 0, -|OH|)$.

$$|OH| = \frac{\frac{V_{length}}{2}}{\tan(\frac{fov}{2})}$$

(3-63)

Then, the coordinates of the updated centre point and two end points of horizontal line is obtained after implementing the pitch and roll transformation. Figure 3-34 illustrates the rotation of horizontal line when the airplane is taxiing and rolling to the right. Because the pitch angle α is less than zero degrees when the airplane is taxiing, the pitch angle of the horizontal line should be $-\alpha$. The rotation axis of pitch is the x-axis and the rotation axis of roll is the z-axis. Thus, the rotation transformation matrix of pitch and roll (T_{Rx2} and T_{Rz6}) are depicted in equations 3-64 and 3-25.

$$\mathbf{T}_{Rx2} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(-\alpha) & \sin(-\alpha) & 0 \\ 0 & -\sin(-\alpha) & \cos(-\alpha) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(3-64)

The coordinates of point H, K and J can be represented by (X, Y, Z). The coordinates of point H₂, K₂ and J₂ are represented by (X_R, Y_R, Z_R). Their relationship is depicted in equation 3-65.

$$\begin{bmatrix} X_R & Y_R & Z_R & 1 \end{bmatrix} = \begin{bmatrix} X & Y & Z & 1 \end{bmatrix} \mathbf{T}_{Rx2} \mathbf{T}_{Rz6}$$

(3-65)

Finally, the horizontal line on the HUD can be drawn by projecting the end points onto the HUD plane. That means one of the updated end points of the horizontal line is the intersections of the line OK₂ with the HUD plane and the other is the intersections of the line OJ₂ with the HUD plane. The HUD projection point of point H₂, K₂ and J₂ are represented by (X_P, Y_P, Z_P). Then, the coordinates of the projection points can be calculated by equation 3-66.

$$\begin{aligned}
 [X_P \quad Y_P \quad Z_P \quad 1] &= [X_R \quad Y_R \quad Z_R \quad 1] \begin{bmatrix} \frac{Z}{Z_R} & 0 & 0 & 0 \\ 0 & \frac{Z}{Z_R} & 0 & 0 \\ 0 & 0 & \frac{Z}{Z_R} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \\
 (3-66)
 \end{aligned}$$

The artificial horizontal line will be generated by linking the projection point of point K_2 and J_2 .

There are several heading markers on the horizontal line. The coordinates of these markers are calculated by rotating the point H around the axes of the attitude indicator coordinate system. The transformation procedure is as following:

First, rotating the y-axis through an angle $\Delta \gamma$. Second, rotating the x-axis through an angle $-\alpha$. Third, rotating the z-axis through an angle β . Fourth, projecting the point onto the HUD plane.

The rotation transformation matrix for rotating the y-axis is depicted in equation 3-67 and the coordinates after rotating can be calculated according to equation 3-68. The angle $\Delta \gamma$ is the difference between the value of the heading marker and the heading of the airplane.

$$\begin{aligned}
 \mathbf{T}_{Ry3} &= \begin{bmatrix} \cos \Delta \gamma & 0 & -\sin \Delta \gamma & 0 \\ 0 & 1 & 0 & 0 \\ \sin \Delta \gamma & 0 & \cos \Delta \gamma & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \\
 (3-67)
 \end{aligned}$$

$$\begin{aligned}
 [X_R \quad Y_R \quad Z_R \quad 1] &= [X \quad Y \quad Z \quad 1] \mathbf{T}_{Ry3} \mathbf{T}_{Rx2} \mathbf{T}_{Rz6} \\
 (3-68)
 \end{aligned}$$

Then, the heading markers and the horizontal line can be drawn according to their coordinates in the attitude indicator coordinate system

In order to display the compass horizontal line on the HUD, the coordinates of the end points of the artificial horizontal line and the heading markers have to be treated by equation 3-69, where the W_s and H_s represent the width and height of the computer screen.

$$\begin{cases} X_s = \frac{W_s}{2} + X_p \\ Y_s = \frac{H_s}{2} - Y_p \end{cases} \quad (3-69)$$

3.3.4 The Guidance and Control Information on the HUD

There are several aspect of guidance information displayed to assist the pilots, such as the guidance line, the position of the own ship, the termination of guidance line and the holding point geometries. The Centre Line Left/Right Caution is displayed as the caution information to remind the pilots taxiing on the centre line of the taxiway. The clearance point geometry is used as the control information sent by the traffic controller.

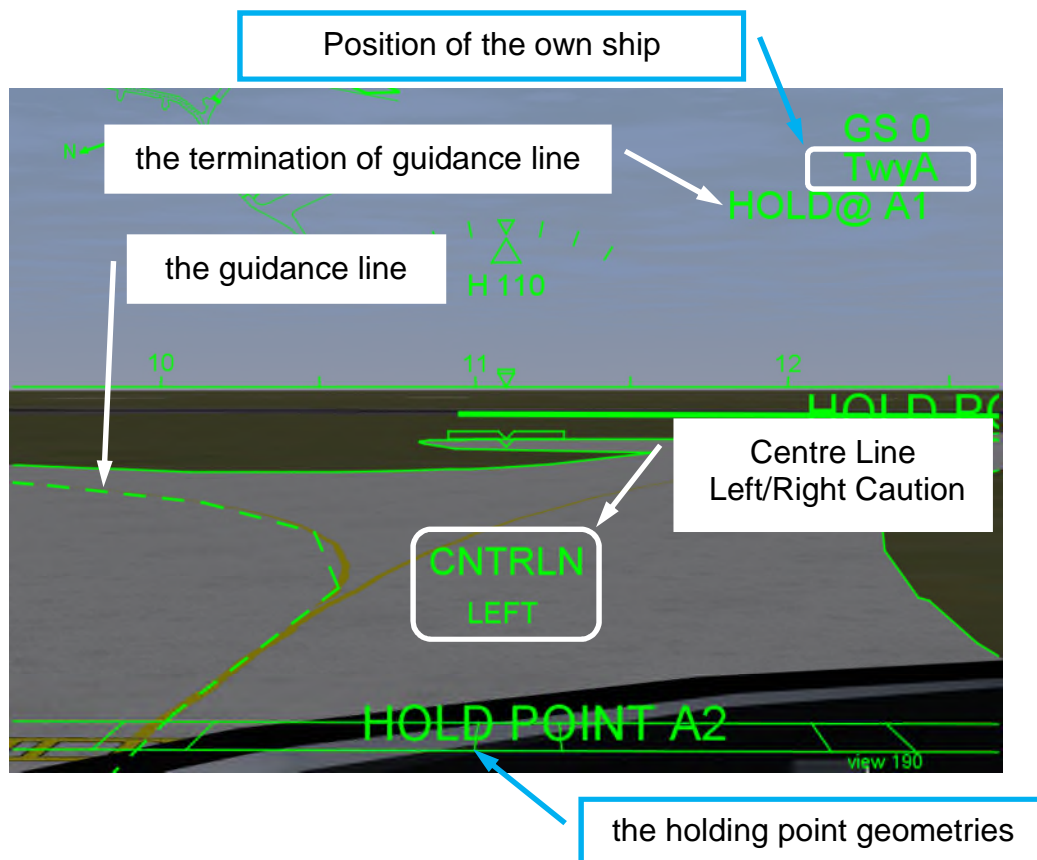


Figure 3-35 The guidance information on the HUD

As shown in Figure 3-35, the airplane is parking at the holding point A2 on the right of the guidance line. The geometry of guidance line is a dash line, the generating method is the same with that of the virtual taxiway. The initial data of the guidance line is generated by the Simulink block called 'CreatGuidance'. The data is constituted by a serial of 3D world coordinates of the points on the guidance line. The position of the own ship is displayed synchronized with the own ship position displayed on the integrated moving map. The holding point geometry is displayed by referring the real holding point markers on the taxiways. The 3D world coordinates of the holding points have to be transformed by performing the 3D viewing process.

Regarding the taxiing velocity and the distance between two adjacent guidance points, the fourth guidance points ahead of the own ship is used to determine the guidance direction. Figure 3-36 illustrates the Centre Line Left/Right Caution strategies. The guidance direction is calculated from the eye point of HUD E to

the fourth guidance point G_4 . There are two reasons to use the eye point of HUD, not the centre of the gravity of the own ship. First, the eye point of HUD is fixed on the own ship, it moves together with the own ship. Second, the visibility of the fourth guidance point will be used as the trigger to display the Centre Line Left/Right Caution. As shown in Figure 3-36, when the fourth guidance point G_4 is outside the visible field of the HUD (the triangle F_1EF_2), the Centre Line Left/Right Caution will be displayed. The value range of the guidance direction and the heading are from 0 degrees to 360 degrees ($0^\circ \leq \text{angle} < 360^\circ$).

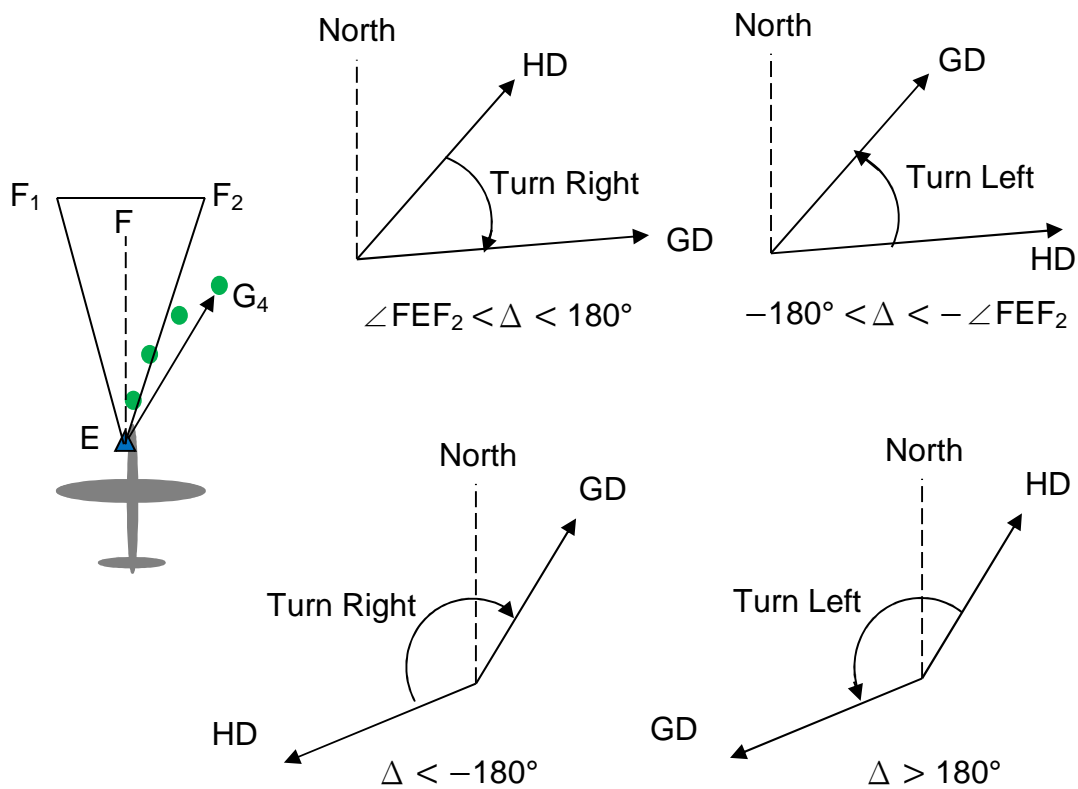


Figure 3-36 The Centre Line Left/Right Caution strategies

The delta Δ represents the difference between the Guidance Direction (GD) and the Heading of the own ship (HD). Their relationship is described in the formula 3-70.

$$\Delta = GD - HD$$

(3-70)

The delta Δ is used to judge the direction of the fourth guidance point and it is also used to judge whether the fourth guidance point is outside the visible field of the HUD. The value of $\angle FEF_2$ is the half value of the $\angle F_1EF_2$ in Figure 3-36. If the fourth guidance point is on the left of the heading direction and it is outside the visible field of the HUD, the Centre Line Left Caution will be displayed on the centre of the HUD to remind the pilots to turn left. If the fourth guidance point is on the right of the heading direction and it is outside the visible field of the HUD, the Centre Line Right Caution will be displayed on the centre of the HUD to remind the pilots to turn right.

When the airplane is taxiing on the guidance line, the taxiway clearance point is used to stop the airplane regardless of where the airplane is. Because there are a serial of guidance points already defined on the guidance line, the guidance points can be used as the clearance points. The clearance point is set according to the GPS position of the own ship. Normally, the clearance point is set 50 meters ahead of the own ship. There are also several options prepared to the traffic controller, such as 50 meters, 100 meters, 150 meters, 200 meters and 300 meters ahead of the own ship. After choosing the position of the clearance point, the 3D world coordinates of the two end points of the clearance bar will be calculated. The HUD will display the clearance bar with a STOP text on the middle of the clearance bar when the clearance bar is visible in the HUD view frustum.

3.4 Traffic Control Simulation

3.4.1 The Airplane Movement Control

There are two computers used in the research: to simulate the own ship and to simulate the console of the traffic controller and control the movement of the other airplanes. Because Simulink can use the net_fdm protocol to access the computer port number 5502 and control the movement of the airplane in FlightGear, each computer can control one airplane in FlightGear using Simulink. Additionally, each computer can use the joystick or keyboard to control another airplane in FlightGear. Thus, four airplanes can be controlled in

the simulation environment. The own ship is controlled by the joystick. The intruder is controlled by Simulink. The Simulink structure of the intruder is shown in Figure 3-37.

The block 'Client1' is used to generate the coordinates in the Ordnance Survey National Grid, when the intruder is controlled to move in alignment with the designated guidance line with a designated velocity. The block 'OSNGtoLLA' is used to transform the coordinates to the latitude and longitude. Because of the convergence of the Ordnance Survey map, the heading of the intruder is also adjusted in the Sum block. The ellipsoid height, roll and pitch are set to constant. Then, the airplane position and rotation information are sent to the following FlightGear Preconfigured 6DoF Animation Block to control the movement of the airplane.

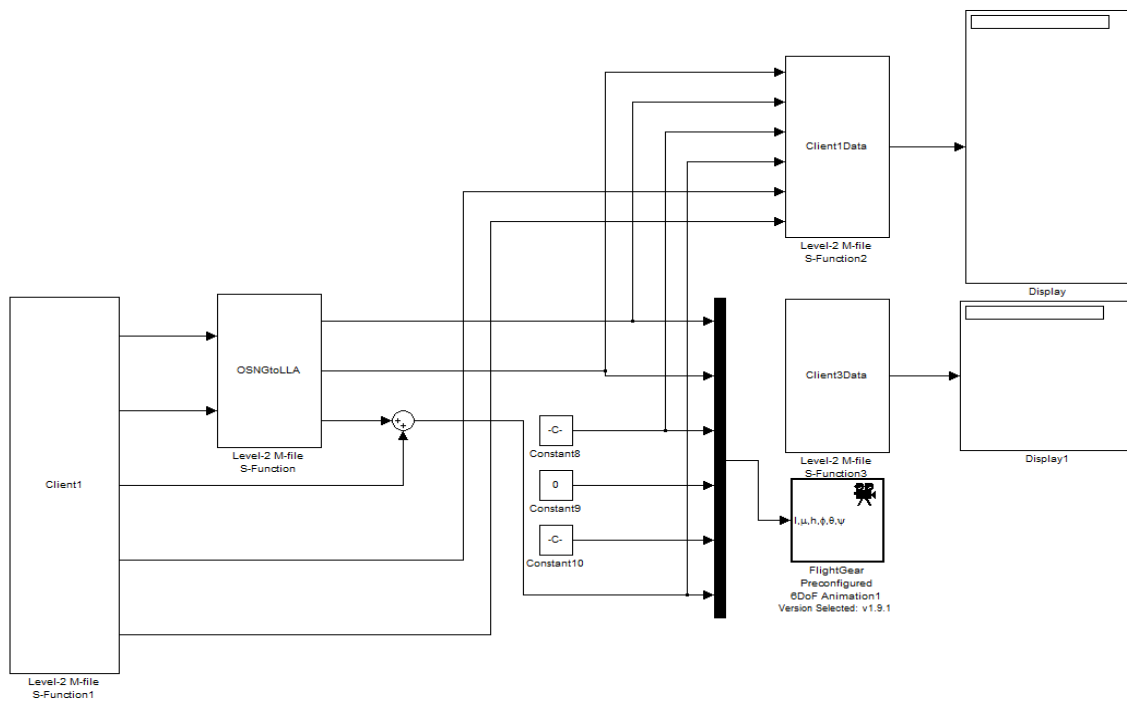


Figure 3-37 The Simulink structure of the intruder movement

3.4.2 Data Communication Between Traffic Controller and Airplane

The internet is introduced to simulate the data communication between the traffic controller and the airplane. Considering the airplane is moving on the airport, one computer with WIFI Network Adapter is used to simulate the own

ship. The free software Apache HTTP Server (version 2.2) is introduced to communicate data between two computers. After opening the HTTP server, each computer can be accessed by other computers from the internet.

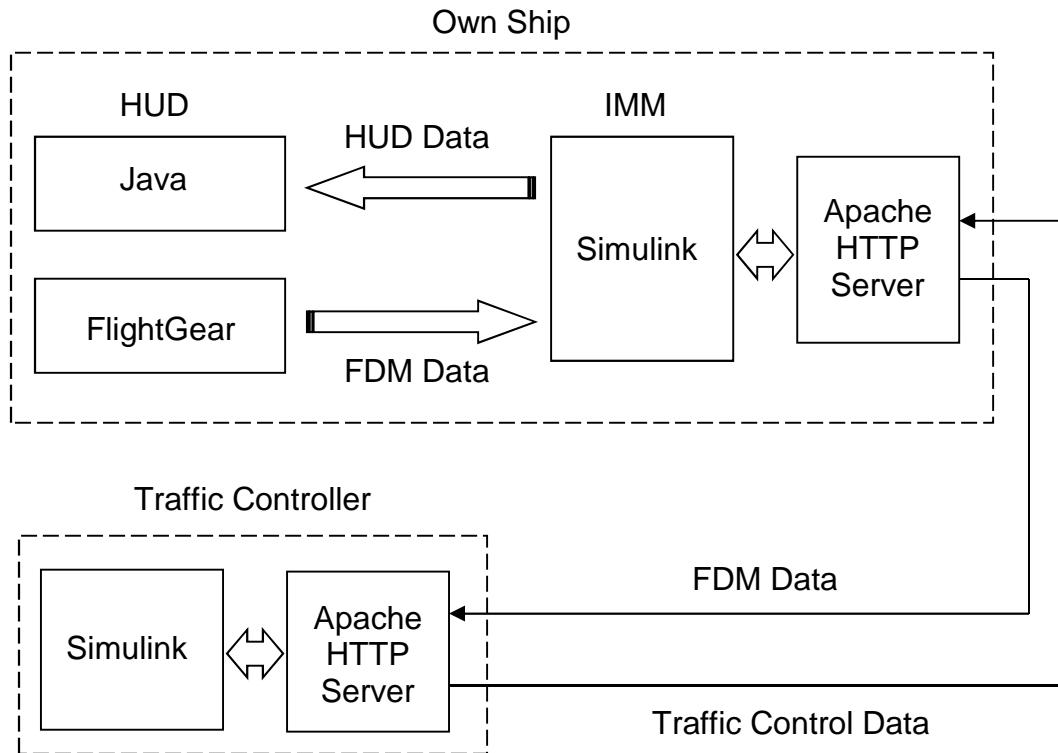


Figure 3-38 The data communication structure

The data communication structure is illustrated in Figure 3-38. For the internal communication in one computer, the data of the Flight Dynamics Model (FDM) is transferred from the FlightGear to the Simulink. Then, the Simulink generates the HUD geometries data and sends them to Java which is used to draw the geometries on the screen. For the outside communication between two computers, the FDM data is transferred from own ship to the traffic controller. The FDM data is used to display the airplane symbol on the traffic control console. It can also be engaged in generating the traffic warning information. The traffic control data is transferred from the traffic controller to the own ship by the Apache HTTP Server. The traffic control data includes the designated guidance line, the runway occupation status and the taxiway clearance data. The simulation structure of the traffic control console is illustrated in Appendix B. The position data of the airplanes on the airport are treated by the block

'Host_info','Client1_info','Client3_info' and 'LLAtoOSNG', then, the map coordinates of the airplanes are sent to the block 'Controller' to display the airplane symbols on the traffic control console.

4 SIMULATION RESULTS AND DISCUSSIONS

4.1 Airport Model

The Cranfield airport model was built and installed in FlightGear. Figure 4-1 shows the screen capture of the model. There is one runway and nine taxiways generated according to the geometries on the Ordnance Survey map. The material of the taxiway is concrete and the material of the runway is asphalt according to the ICAO aerodrome chart. There are five Aprons built for parking airplanes. Each yellow taxiway centre line was generated to guide the taxiing. There are in total sixteen holding points; the designators and geometries of the holding points are listed in the Table 4-1.

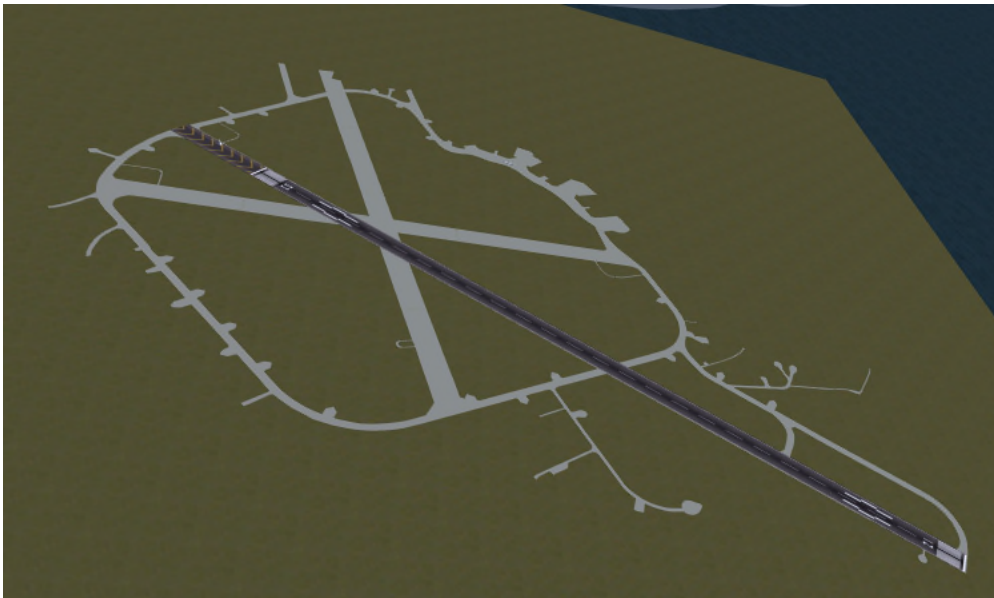




Figure 4-1 The Cranfield airport 3D model

Table 4-1 The Holding Point Designators And Geometries

Designators	Geometries	Type Of Marking
A1, B1, C1, A3, A4, D1, E1, F1, G1, H1, K1, L1		Holding Position
A2, E2, F2, G2		ILS Critical Area

4.2 Head Down Display Simulation

The IMM displayed on the head-down display system was generated by Simulink. Figure 4-2 illustrates the general layout of the IMM. There are two main regions on the layout: the graphics region, which displays the moving map, airplane symbols and other guidance graphics, and the control region, which contains control buttons, sliders and text information.

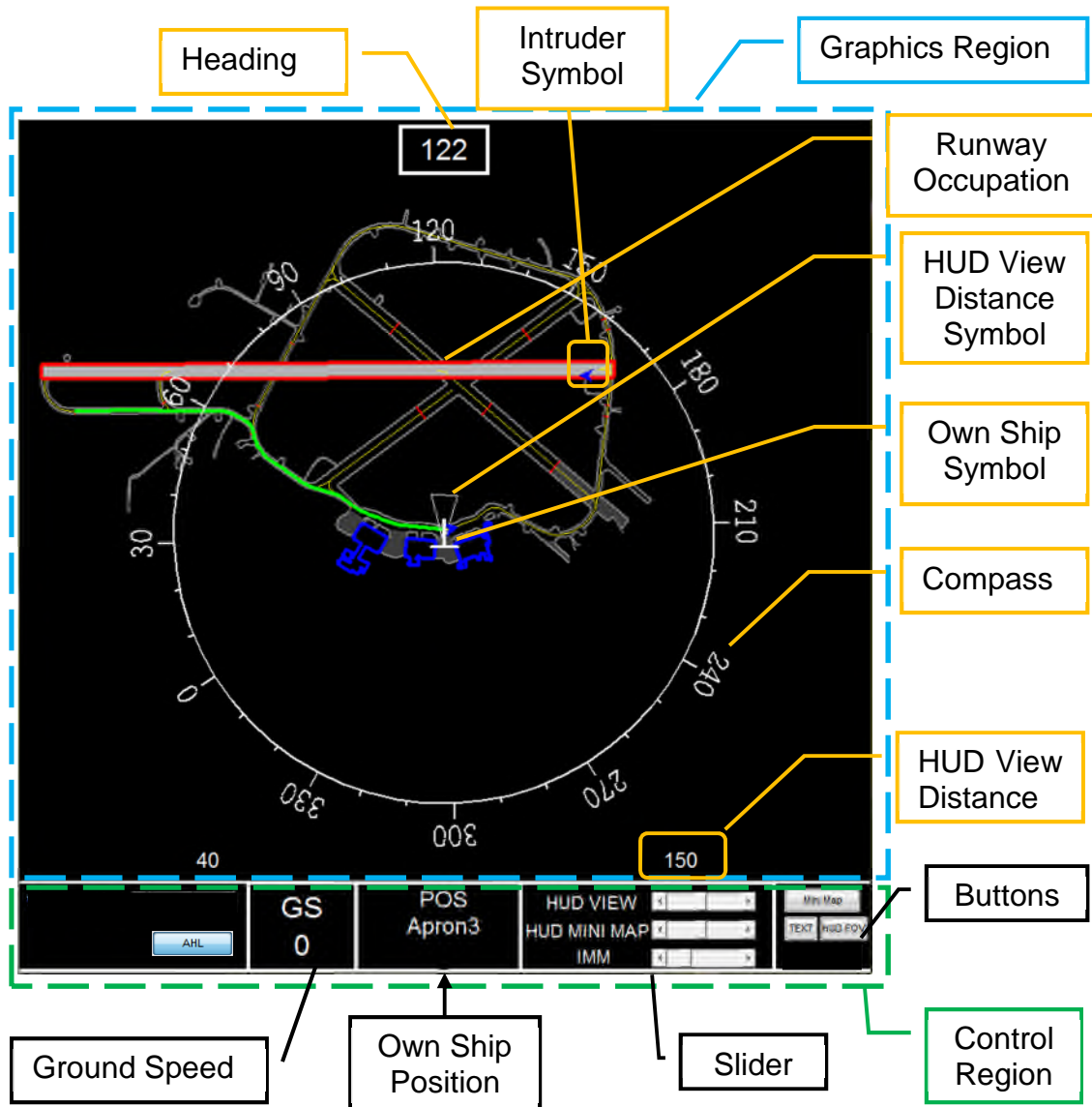


Figure 4-2 The general layout of the IMM

The background colour of the IMM is black, as this colour provides a high image contrast on the head-down display. The own ship symbol is located in the

centre of the graphics region, and is represented by the two white intersecting line segments.

In the graphics region, the moving map is composed of the grey edges of the runway and the taxiways, the yellow taxiway centre lines, the grey apron polygons, the blue hangar polygons, the red holding points and the green guidance line. The intruder symbols are also located on the moving map. All the graphics located on the moving map can be moved together with the map. The compass is displayed to assist the pilots awareness of the directions on the map. It will rotate according to the heading of the own ship.

There is an important rectangle coincident with the edge of the runway. When the traffic controller sets the runway occupation status to 'Runway Occupied' manually, the own ship will display the rectangle in red to prevent the own ship taxiing onto the runway. Until the runway occupation status is 'Runway Clearance', the red rectangle will disappear.

There is a useful HUD view distance symbol ahead of the own ship symbol. It is used to show the visible distance of the HUD, in other words how far the virtual taxiways and guidance lines will be displayed on the HUD. The HUD view distance symbol is represented by a triangle whose size is controlled by the visible distance of the HUD. Additionally, the symbol size can also be controlled by the zoom-in and zoom-out functions of the moving map.

The green guidance line on the IMM is the most important graphic for guiding the taxiing; it is designated by the traffic controller and indicates the taxiing directions. In Figure 4-2, the guidance line indicates the taxiing direction along the taxiway A from Apron 3 to the holding point A1. Because the guidance line is sent by the traffic controller, in order to display the same designated guidance line, the same database of the guidance lines was installed and called by the own ship and the traffic controller.

In the control region, there are three control sliders and three control buttons. The first control slider called 'HUD VIEW' is used to control the visible distance of the HUD. The distance range is from 30 meters to 300 meters. When sliding

the block on the slider, the value of the visible distance which is displayed above the slider will be changed simultaneously. This benefits the pilots to adjust the visible distance of the HUD.

The second control slider named 'HUD MINI MAP' is used to achieve the zoom-in and zoom-out function of the HUD mini map by controlling the 'fov' of the eye coordinate frame of the HUD mini map. The third control slider called 'IMM' presides the zoom-in and zoom-out function of the IMM.

In addition, the three control buttons are used to control the visibility of symbols and text. When pressing down the first button 'Mini Map', the HUD mini map will be displayed on the HUD. When pressing the first button again, the HUD mini map will disappear. The other two buttons control the visibility of the text of the taxiway designator and the HUD view distance symbol on the IMM.

4.3 Head-Up Display Simulation

The head-up display is a transparent graphic generated by Java. It is used to assist the pilots taxiing on the taxiway, especially in low visibility weather conditions.

As shown in Figure 4-3, the airplane is taxiing near the holding point A1 in low visibility weather conditions. In order to simulate the real HUD, the colour of all the geometries on the HUD is set to green. The geometries of the virtual taxiway is coincident with the edges of the taxiway in FlightGear. Thus, the pilots can image the outside taxiways according to these virtual taxiways.

The guidance line is a dash line which is coincident with the taxiway centre line. The airplane should taxi to align the guidance line to the destination. The HUD mini map is displayed in the top left corner of the HUD, the own ship is represented by a cross and the airport moving map is displayed under the cross. There is also a dash line on the HUD mini map to represent the guidance line. Then, the pilots do not need to search the position of the own ship from the head-down display as they can obtain the position of the own ship directly from the HUD. It may improve the taxiing security by paying more attention outside the cockpit.

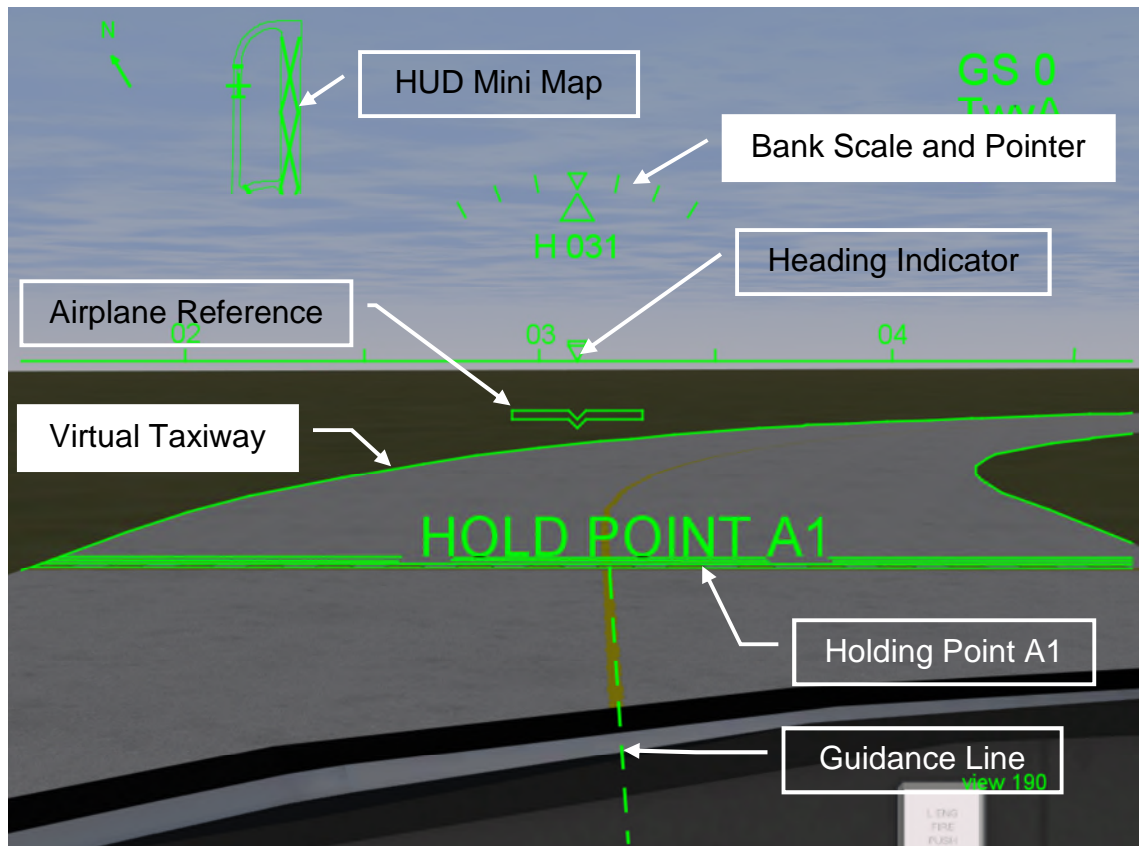


Figure 4-3 The HUD geometries in low visibility weather conditions

The compass horizontal line is generated to improve the pilots' sense of direction and enhance the realism of the virtual taxiways in low visibility weather conditions. The heading markers on the compass horizontal line indicate the directions ahead of the airplane. It is displayed in five degree increments and labelled every 10 degrees on the horizontal line. The heading indicator is a downward pointing triangle which indicates the current heading on the compass horizontal line. The airplane reference is fixed in the centre of the HUD, and the top centre point of the symbol represents airplane projected centreline. The airplane reference is below the compass horizontal line in taxiing phases, because the pitch is minus degrees. The distance from the top centre point of the symbol to the compass horizontal line represents the value of pitch angle. The Bank Scale and Pointer displays the corresponding roll attitude in ten degree increments between 0° and $\pm 30^{\circ}$. The digital heading displays current heading directly below the roll scale pointer. The digital ground speed displays the current digital ground speed. The own ship position is displayed directly

under the digital ground speed. The holding point A1 is represented by two solid lines and two dash lines on the virtual taxiway. The designator of the holding point is displayed on the top of the holding point symbol. The holding point on the virtual taxiway benefits the pilots to pay attention to the holding point ahead of the airplane and avoid passing the holding point if it is the taxiing destination.

After evaluation by the pilots, some pilots suggest to cancel the compass horizontal line, the heading markers, the heading indicator and the Bank Scale and Pointer to simplify the information displayed on the HUD. A switch on the IMM is designed to provide an option to display or delete these symbols.

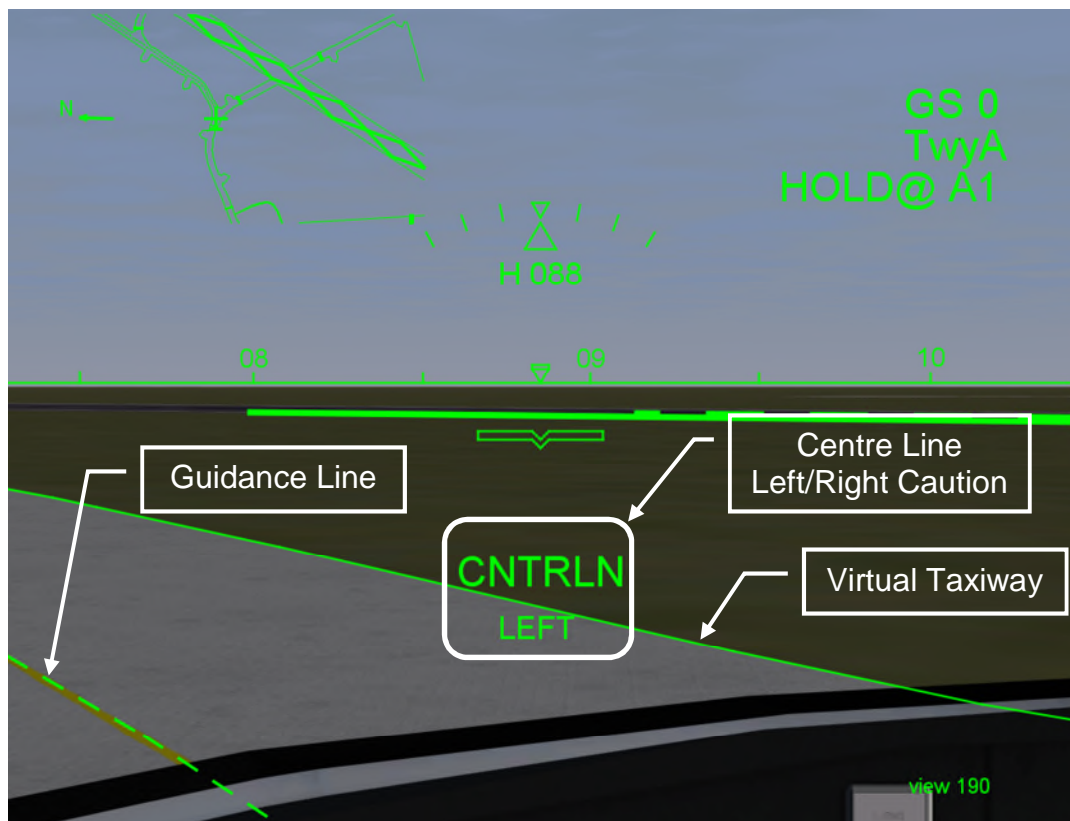


Figure 4-4 The caution information displayed on the HUD

Figure 4-4 illustrates the caution information displayed on the HUD when the guidance line is moving to the corner of the HUD. The Centre Line Left/Right Caution is displayed because the fourth guidance point is outside the view field of the HUD. The pilots can take actions, such as left/right turn according to the caution information.

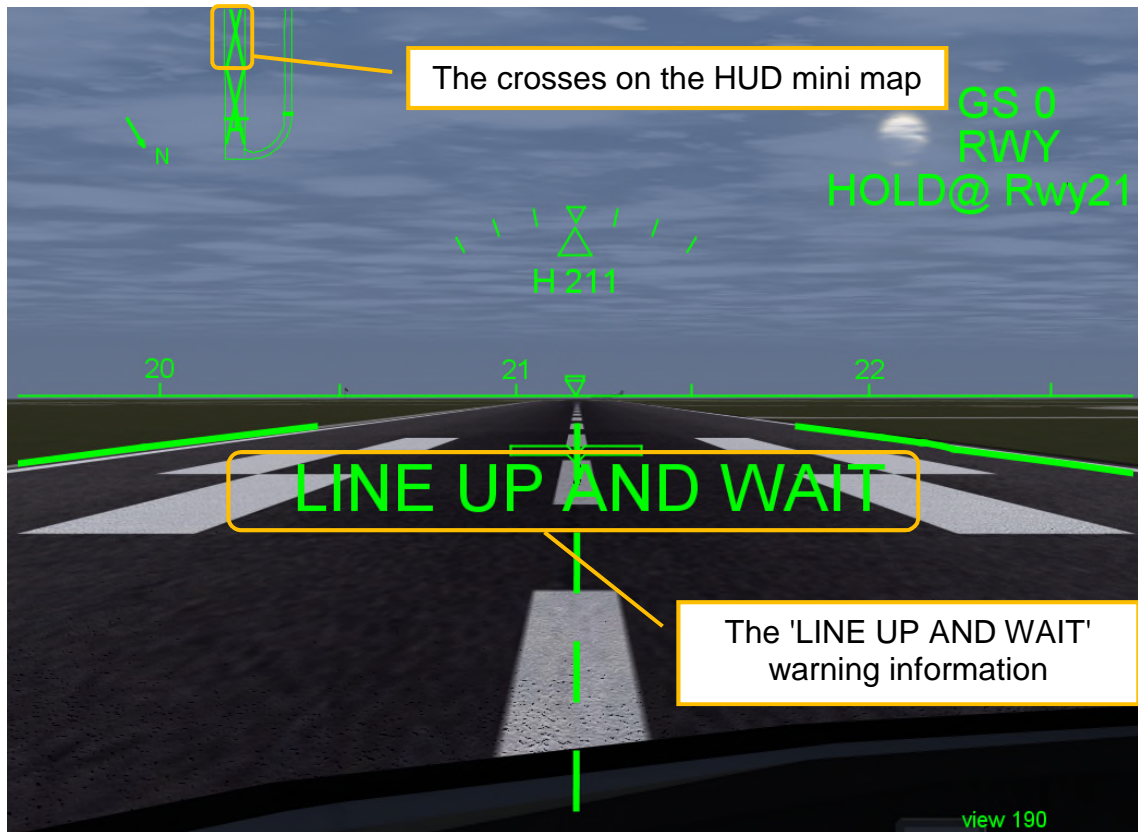


Figure 4-5 The runway occupation symbols on the HUD

The runway occupation symbols on the HUD mini map is several crosses on the runway. They represent that the runway is occupied by other aircraft. As shown in Figure 4-5, the own ship is on the runway already occupied by the other airplane; there are several thick crosses on the HUD mini map and 'LINE UP AND WAIT' warning information displayed on the HUD to prevent the takeoff [43]. Simultaneously, the HUD mini map displays the crosses on the runway.

As illustrated in Figure 4-6, when the ATC issues the takeoff clearance, the 'CLEARED FOR TAKEOFF' information will replace the 'LINE UP AND WAIT' warning information in the centre of HUD to authorize the airplane to depart [43]. Simultaneously, the crosses on the runway of the HUD mini map will disappear.



Figure 4-6 The 'CLEARED FOR TAKEOFF' authorization on the HUD

The taxiway clearance bar is a thick straight line segment normal to the guidance line. It is not painted on the real taxiway, but it is designated by the traffic controller when he needs the specified airplane to stop at the specific position on the taxiway. As shown in Figure 4-7, there is a 'ATC HOLD' mark displayed on the top centre of the clearance bar and a red clearance bar will be displayed ahead of the airplane symbol on the IMM. The guidance line behind the clearance bar will be disappeared automatically in order to avoid the pilot taxiing cross the hold point. The pilots should not pass the clearance bar when taxiing the airplane. After the clearance bar was cancelled by the traffic controller, the clearance bar and the 'ATC HOLD' mark will disappear, and the disappeared guidance line will display again. Then, the pilots are permitted to pass the previous clearance bar.

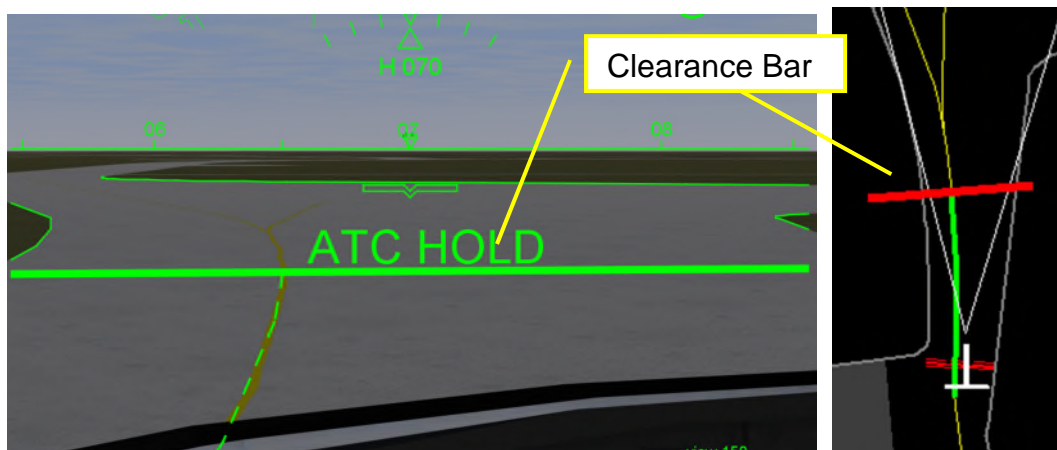


Figure 4-7 The clearance bar on the HUD

As shown in Figure 4-8, if the airplane passes the clearance bar without cancelling the clearance bar by the traffic controller, the 'STOP' mark will be displayed in large text size on the centre of the HUD until the clearance bar is cancelled or reset by the traffic controller. Because the 'STOP' mark is a higher level warning information, it will cover the Centre Line Left/Right Caution which may display on the centre of the HUD.



Figure 4-8 The 'STOP' warning

The terminology of the above guidance information and clearance information is summarized in Table 4-2.

Table 4-2 The Guidance and Clearance Terminology

Terminology	Information Type	Description
HOLD POINT XX	Guidance Information	Holding Point indicator, for example, HOLD POINT A2 means the Holding Point A2.
Twy X	Guidance Information	Taxiway indicator, for example, Twy A represents the Taxiway A.
CNTRLN LEFT	Guidance Information	Centre Line Left Caution is displayed because the fourth anterior guidance point is on the left of the view field of the HUD. Normally, the pilots will turn left to align the airplane with the guidance line according to the caution information.
CNTRLN RIGHT	Guidance Information	Centre Line Right Caution is displayed because the fourth anterior guidance point is on the right of the view field of the HUD.
ATC HOLD	Clearance Information	Clearance bar indicator, located on the top centre of the clearance bar set by the ATC.
STOP	Clearance Information	The 'STOP' warning information, displayed on the centre of the HUD if the airplane passed the hold point without the permission from the traffic controller.
LINE UP AND WAIT	Clearance Information	The warning information to inform a pilot to taxi onto the departure runway to line up and wait. It is used when takeoff clearance cannot immediately be issued because of traffic or other reasons [43].
CLEARED FOR TAKEOFF	Clearance Information	ATC authorization for an aircraft to depart [43].

4.4 Traffic Control Console

Compared to the IMM, the traffic control console is operated by the traffic controller. It is an airport map with a North arrow, the map adjustment functions and traffic control functions. The airport map can be moved, rotated, magnified and diminished manually by the traffic controller.

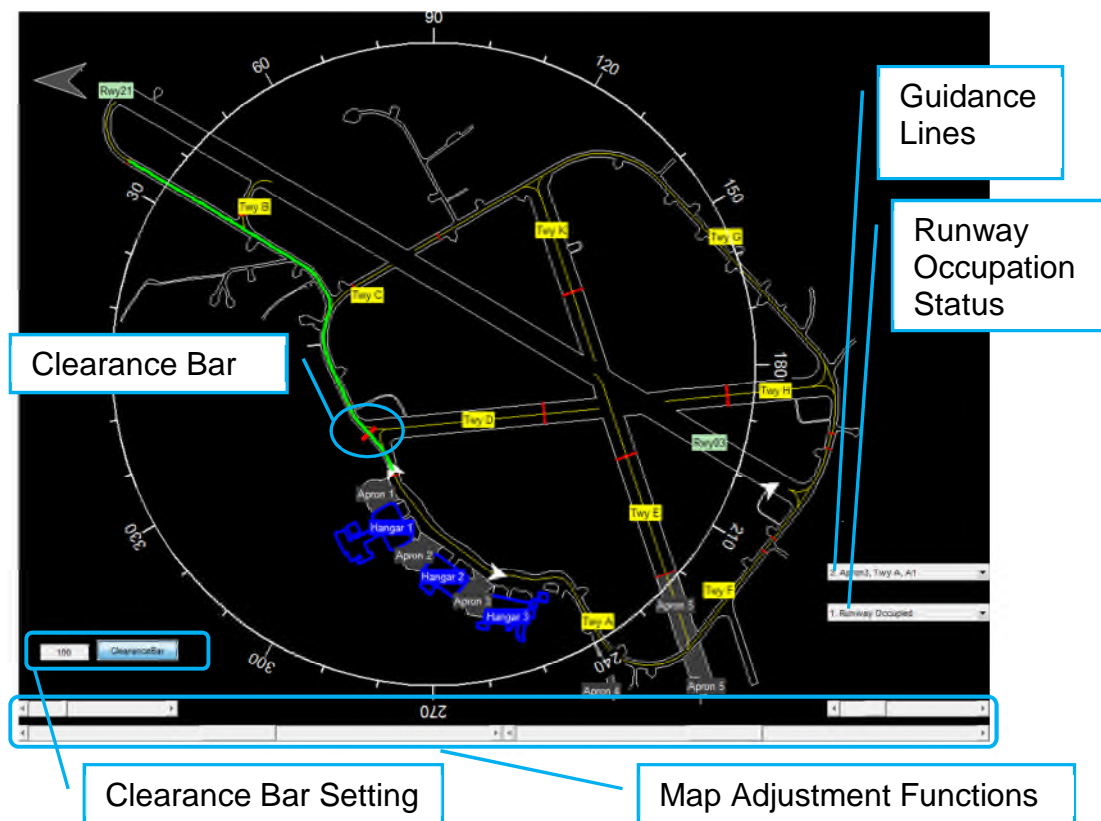


Figure 4-9 The traffic control console

The general layout of the traffic control console is shown in Figure 4-9. The guidance line is set in the popup list, where there are several pre-organised guidance lines. The runway occupation status is set in another popup list which contains two options: the 'Runway Occupied' option and the 'Runway Clear' option. When the runway occupation status is set to the 'Runway Occupied' option, the rectangle edge of the runway on the IMM will be displayed in red. The taxiway clearance bar is set by an editable text box and a trigger button. The distance in the editable text box means the taxiway clearance bar on the

guidance line will be set this distance ahead of the designated airplane. The coordinates of the clearance bar will be sent to the designated airplane.

4.5 Discussions

The pilots were invited to evaluate the HUD surface guidance system. They suggested to add the north arrow on the HUD mini map and move the mini map from the bottom to the top-left corner on the HUD, adding the position of the own ship under the digital ground speed and displaying the clearance point on the HUD. They agreed that the HUD view distance symbol on the IMM was very useful for linking the virtual taxiways on the HUD with the IMM, the control sliders and buttons provided the freedom to adjust the IMM and the HUD. The above pilots' suggestions have been implemented in the updated simulation.

The HUD takeoff mode is not designed in the research. When the pilot receives the runway clearance to depart, the HUD will be set to takeoff mode as illustrated in Figure 4-10. The speed scale and altitude scale will display on the left and right side of the HUD.



Figure 4-10 The HUD takeoff mode [44]

According to the simulation result, the outside sceneries displayed on the HUD may benefit the pilots to taxi in low visibility weather conditions. Compared to the previous research by NASA, the HUD mini map was added to enhance the direction awareness and the HUD view distance can be adjusted to suit the pilots habits. One problem found in simulation is the HUD refresh rate is too low. After analysing this problem, three causes were identified. First, there are nearly five thousand points requiring treatment in the 3D viewing process. Second, the cycle of catching the FDM data from FlightGear may be too long. The solution may be to use a more powerful computer to simulate the HUD and the IMM of the own ship. Possibly a faster approach to catching the FDM data from FlightGear needs to be developed. Third, the view transformation using Matlab may be an another reason for low computational efficiency. Java may be more efficient than Matlab in view transformation.

5 CONCLUSIONS AND FUTURE WORK

5.1 Summary of the Research

The research presented in this thesis has developed a novel on-board scene-linked approach for HUD surface guidance system. In order to achieve a more advanced and reasonable HUD surface guidance system, a literature review about the current surface guidance system was performed. The efficiency of the previous surface guidance methods clearly needs enhancing. Thus, the following tasks were achieved in the research:

Firstly, a simulation environment with an airport model was established.

Secondly, a head-up display framework with more efficient symbols and cautions for surface guidance in airport was developed and the head-up display was integrated with the head-down display.

Thirdly, a traffic control console was developed to control the surface movement by sending the guidance line and taxiway and runway clearance to the airplane.

Finally, the surface guidance system was evaluated by the pilots and updated according to the pilots' suggestions.

5.2 Conclusive Remarks

The following general conclusions were reached:

The HUD view distance symbol on the IMM is very useful to link the virtual taxiways with the IMM. The pilots can conveniently compare the virtual taxiways on the HUD with the IMM.

A methodology to display the virtual taxiways, guidance lines and holding points on the HUD based on the Ordnance Survey airport map is developed. The HUD virtual taxiways, guidance lines and holding points can coincide with the taxiway edges, taxiway centrelines and holding points outside the cockpit from the viewpoint of the captain. The HUD virtual taxiways and guidance lines create an intuitive outside scene for guidance. The guidance line helps the pilots to efficiently find the designated guidance route and avoid confusion with other

taxiway centre lines. The HUD mini map is useful to increase pilot awareness of the position of their own ship without searching for it from the IMM, especially assisting the pilots aware the runway occupation status with several crosses on the runway.

The Centre Line Left/Right Caution information on the HUD reminds pilots to align the airplane with the guidance line. This assists the pilots to keep taxiing on the designated route. As the level of caution information is lower than the warning information, the Centre Line Left/Right Caution information will be covered by the STOP warning information when the airplane passing the hold point without permission from traffic controller.

The virtual taxiway clearance bar displayed on the HUD provide an accurate and prompt control for the taxiway clearance. It assists the pilots to avoid mistake by popping up a large size of 'STOP' warning information on the centre of HUD if pilots passed the hold point without the permission from the traffic controller. The runway occupation symbols give a timely warning to the pilots and prevent them taxiing onto the runway if the runway is occupied by other airplanes.

5.3 Future Work

Future works may be described in the following pragmatic terms:

- Improve the cycle of catching FDM data from FlightGear by researching a more efficient approach. The other FlightGear I/O protocols may need to be analysed.
- Insert the traffic warning information into the system to enhance the security of the surface movement. The symbol of intruder on the HUD may be developed to raise pilot awareness.
- Perform the system test on a real airport, using the GPS receivers as the data input instrument of the system. The other FDM data, such as pitch, roll and yaw, may be obtained from the aircraft gyro.

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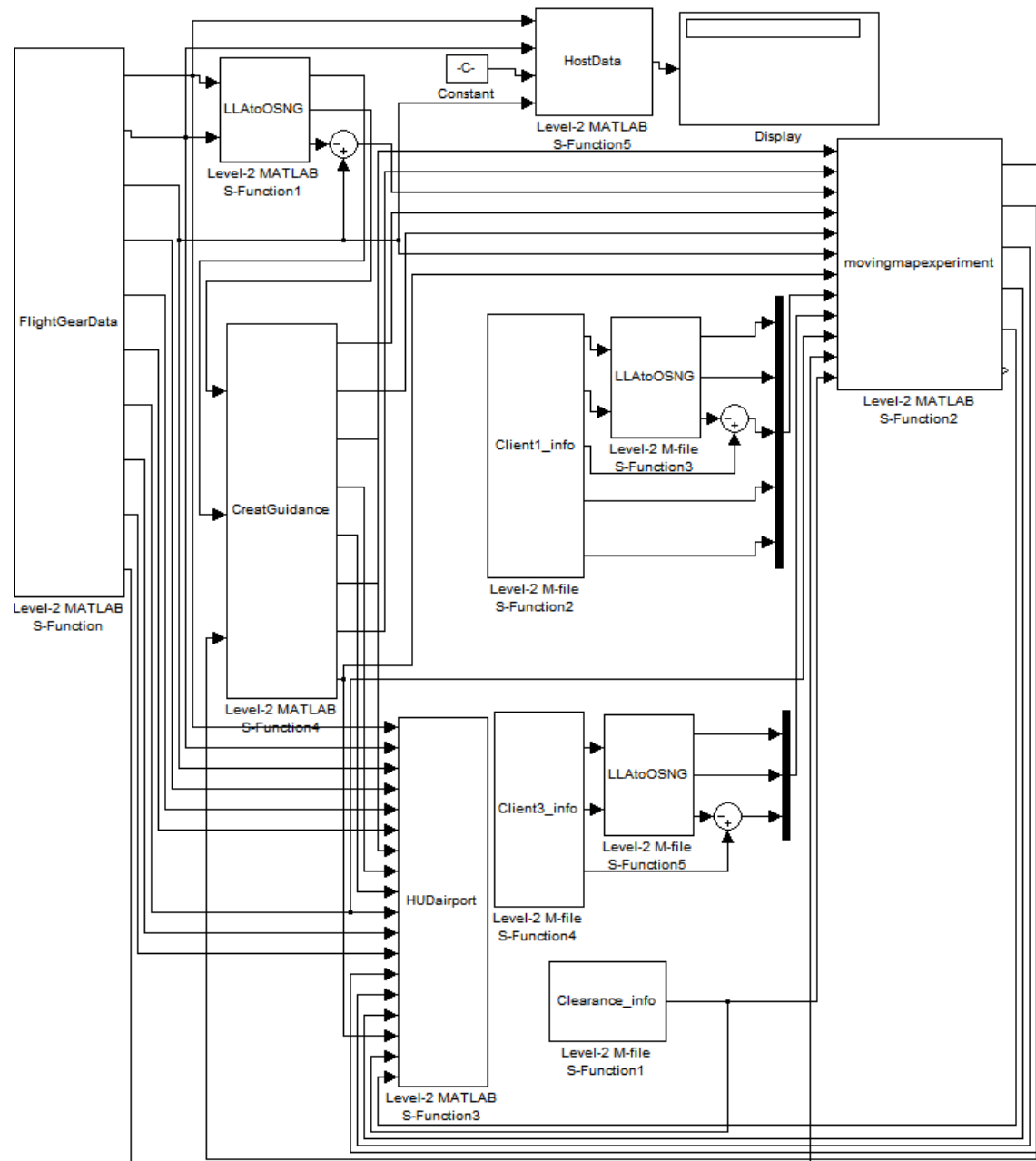
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APPENDICES

Appendix A

Simulation Structure of the SGS Installed in the Airplane



Appendix B

Simulation Structure of the Traffic Control Console

